

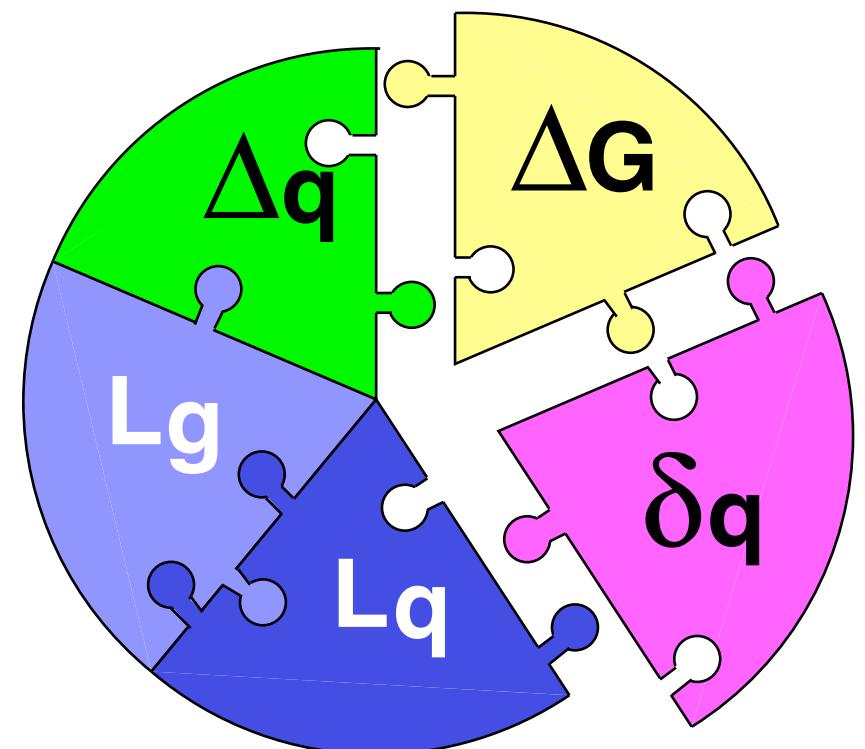
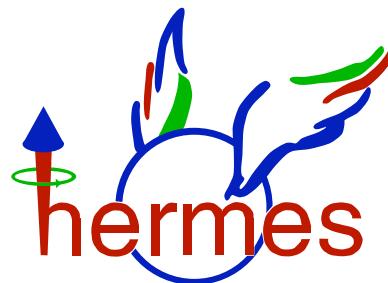
# HERMES: Outlook to 2007

N.C.R. Makins

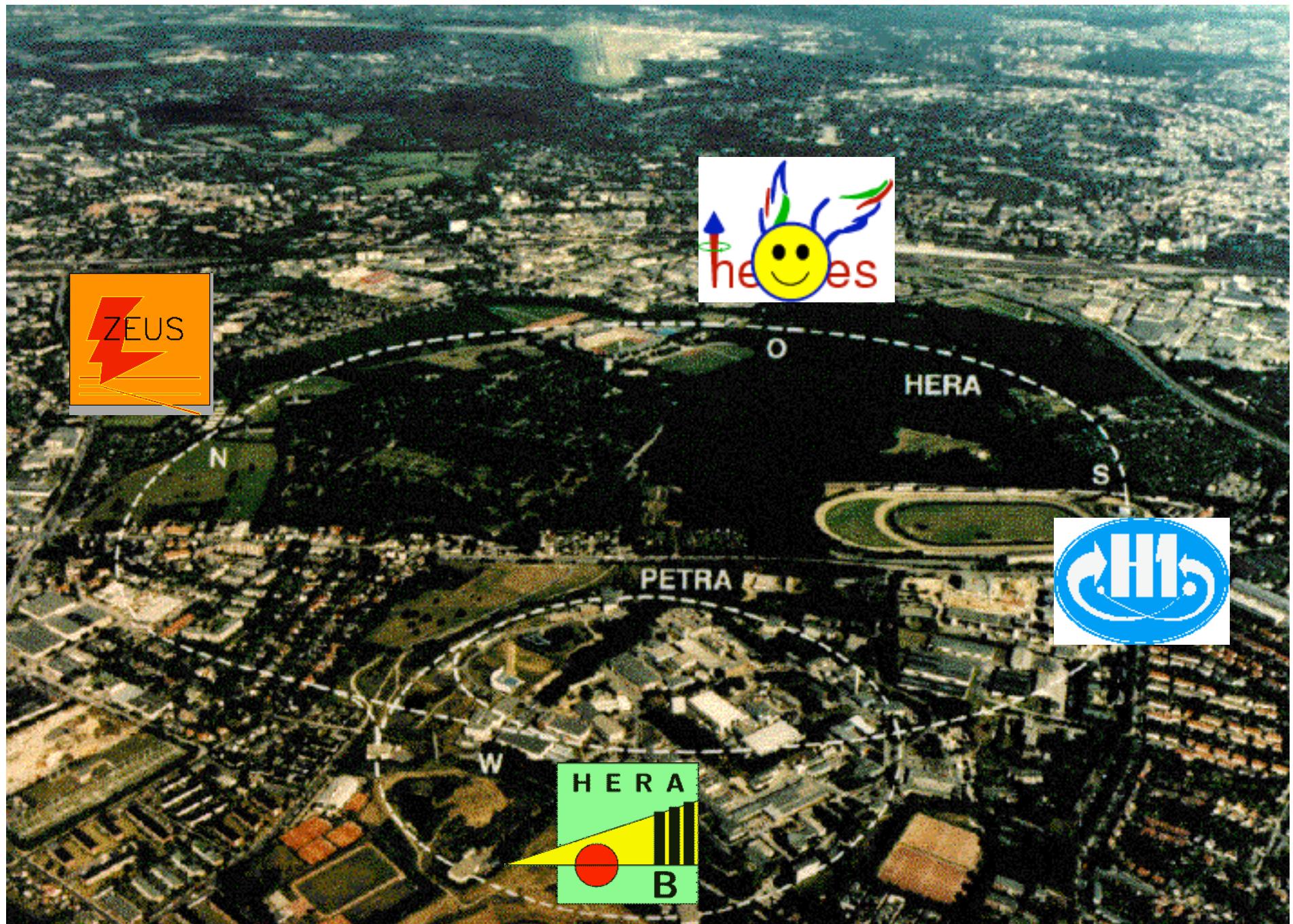
University of Illinois at Urbana-Champaign  
Spin Workshop, BNL, Jun 21, 2005

## The HERMES Roadmap

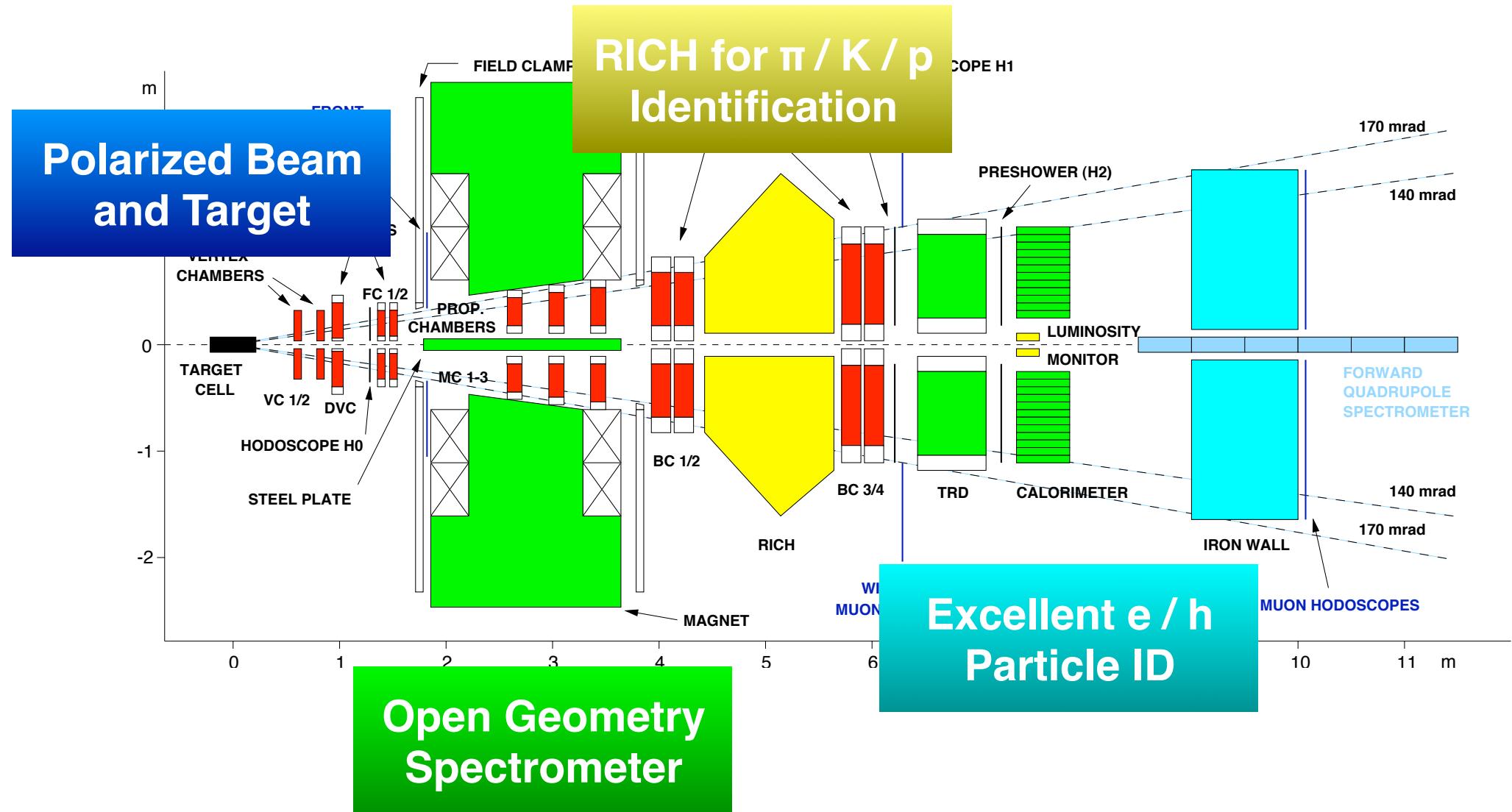
- **Run 1:** 1995 - 2000  
*longitudinal targets*  
focus on **quark polarization**
- **Run 2a:** 2002 - 2005  
*transverse target*  
focus on **transversity & co.**
- **Run 2b:** 2006 - 2007  
*recoil detector*  
focus on **GPD's ... and L!**



**HERMES, at the HERA storage ring** → 27 GeV  $e^+$  /  $e^-$  + 800-900 GeV  $p$   
DESY, Hamburg

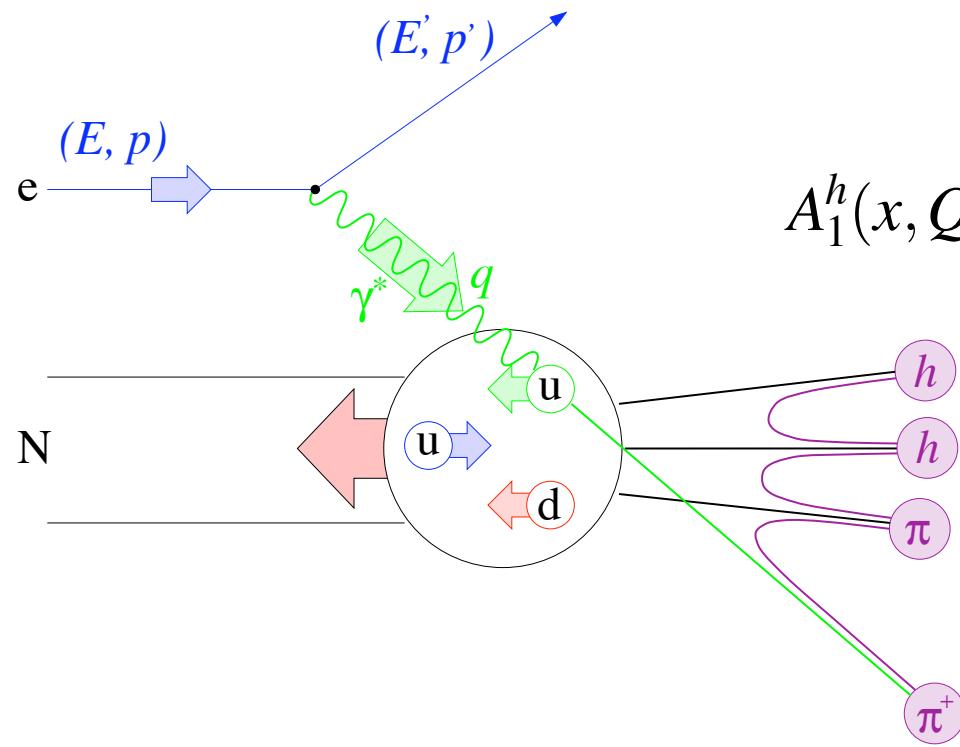


# The HERMES Experiment



# Run 1: Quark Polarization from Semi-Inclusive DIS (SIDIS)

In SIDIS, a hadron  $h$  is detected in coincidence with the scattered lepton:



## Flavor Tagging

Flavor content of observed hadron  $h$  is related to flavor of **struck quark  $q$**  via the **fragmentation functions  $D$**

$$A_1^h(x, Q^2) = \frac{\int_{z_{min}}^1 dz \sum_q e_q^2 \Delta q(x, Q^2) \cdot D_q^h(z, Q^2)}{\int_{z_{min}}^1 dz \sum_q e_q^2 q(x, Q^2) \cdot D_q^h(z, Q^2)}$$

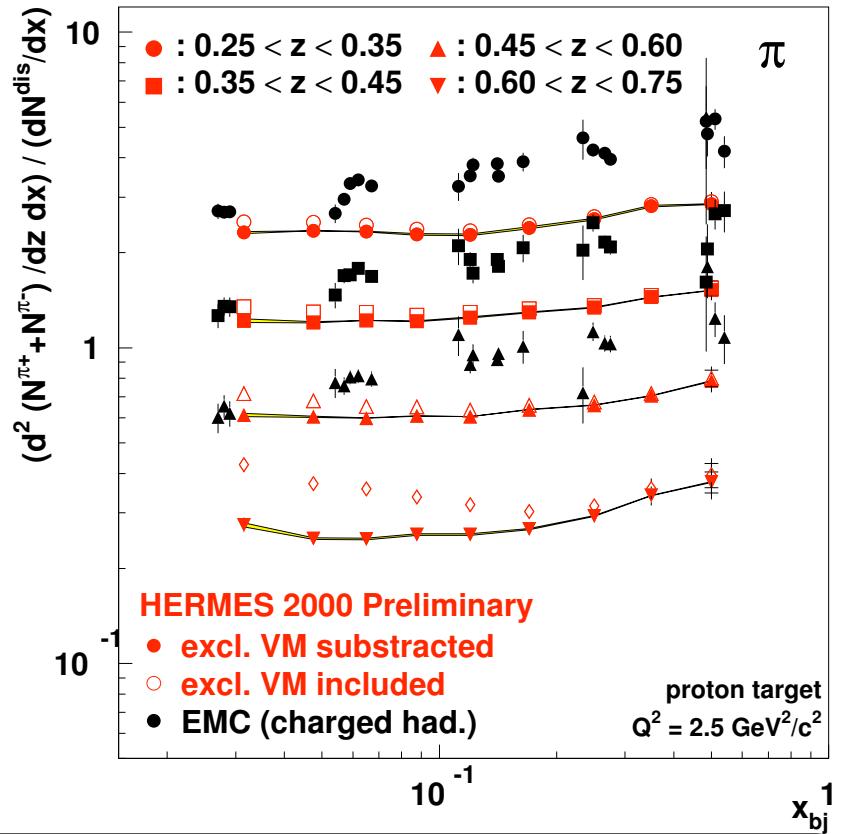
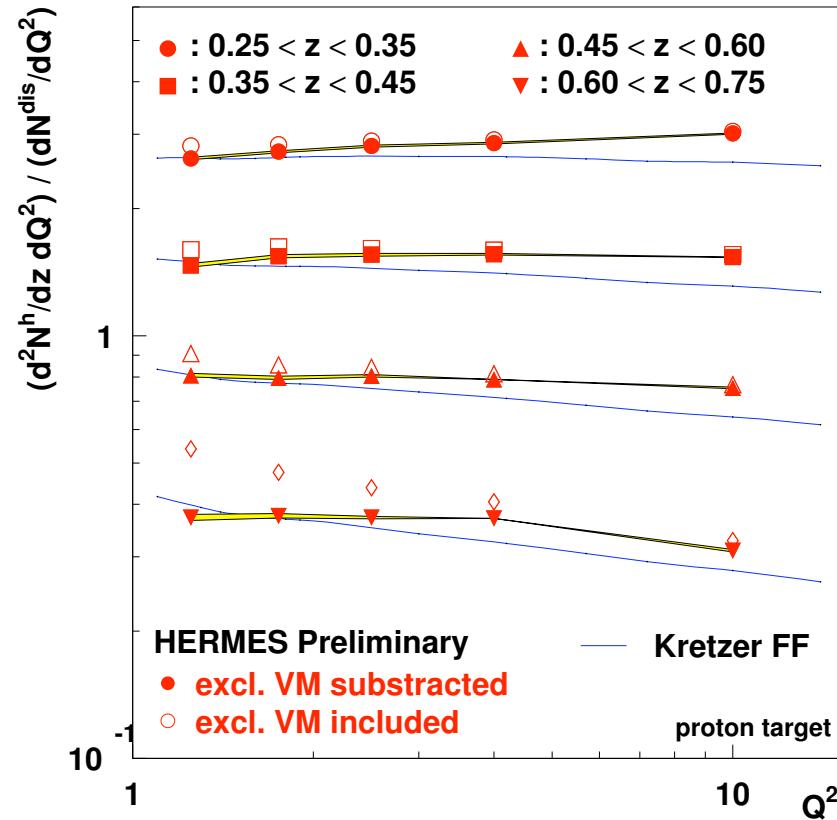
Rewriting ...

$$A_1^h(x, z) = \sum_q P_q^h(x, z) \frac{\Delta q(x)}{q(x)}$$

**Purity matrix  $P_q^h$**  = probability that hadron  $h$  came from struck quark  $q$

Purities are spin-independent ... compute using Monte Carlo

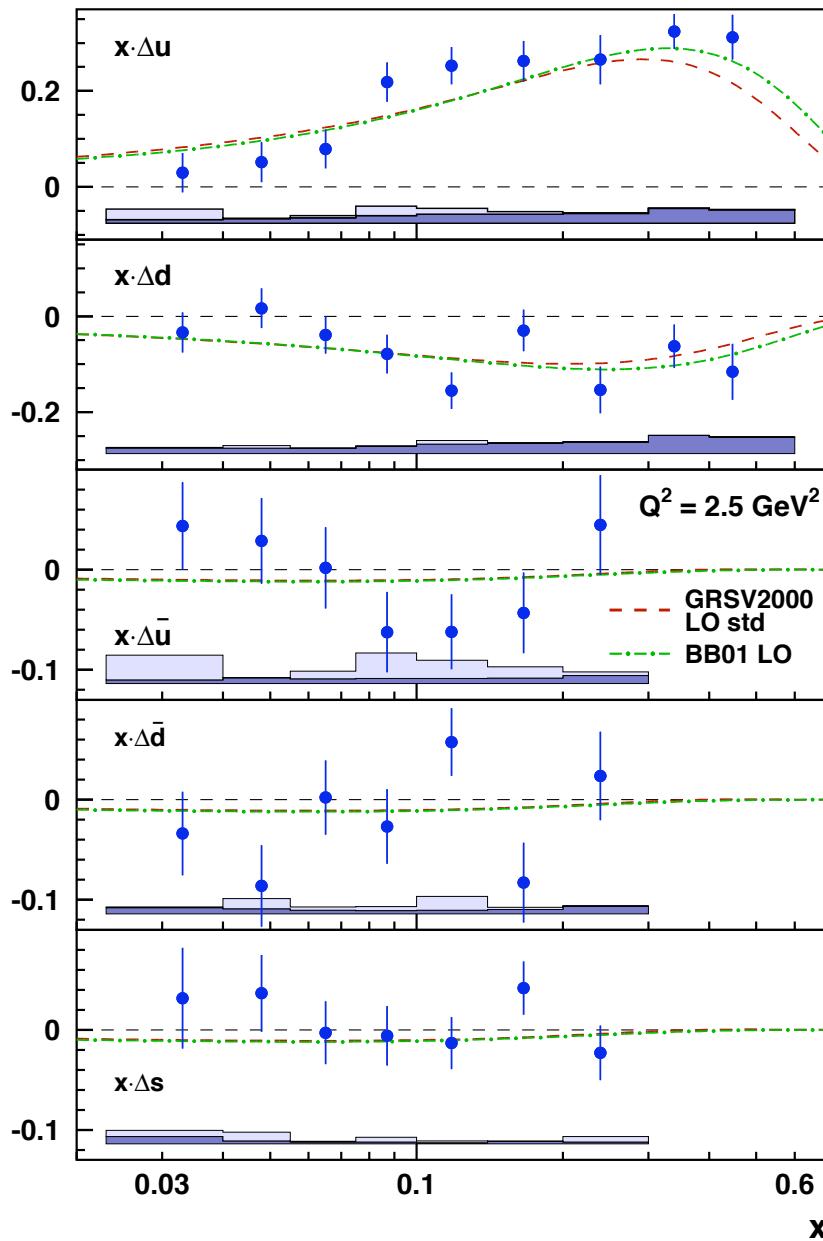
$$\frac{1}{N_{\text{DIS}}} \frac{dN^{(\pi^+ + \pi^-)}}{dz} = \frac{(4u + d + 4\bar{u} + \bar{d})(D_1 + D_2) + 2(s + \bar{s})D_s}{(4u + d + 4\bar{u} + \bar{d}) + (s + \bar{s})} \approx D_1(z) + D_2(z)$$



Good agreement with  $e^+e^-$  fragmentation functions measured at much higher energy scales! & very weak  $x$ -dependence of extracted FF's: **factorization working well!**



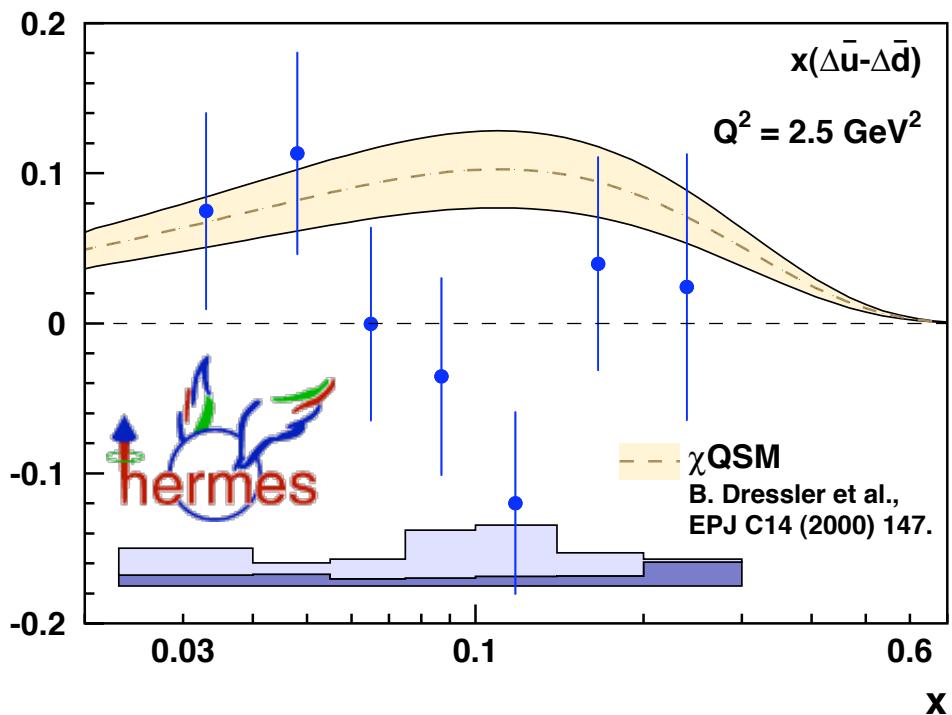
# Final HERMES $\Delta q$ Measurement from SIDIS



- input:  $A_{1,p}$ ,  $A_{1,p}^{\pi^\pm}$ ,  $A_{1,d}$ ,  $A_{1,d}^{\pi^\pm}$ ,  $A_{1,d}^{K^\pm}$
- Assumption:  $\Delta \bar{s} = 0 \pm 1/\sqrt{3}$
- **First 5-flavor fit to  $\Delta q(x)$**
- **No significant  $\bar{q}$  polarization seen**  
... but ...
- Results **perfectly consistent** with **inclusive** fits  $\Rightarrow \chi^2/\text{dof} = 0.6 - 1.6$  vs BB (SU3-sym) **and** GRSV-valence ☺
- In **measured range** ( $x = .023 - .6$ ),
  - $\int \Delta \bar{u} = -0.002 \pm 0.043$
  - $\int \Delta \bar{d} = -0.054 \pm 0.035$
  - $\int \Delta s = +0.028 \pm 0.034$

## Flavor-Asymmetry of Sea

Comparison with Chiral-Quark Soliton  
Model calculation “not great” ...



Lack of flavor-asym  $\Delta\bar{u} \neq \Delta\bar{d}$  more reminiscent of ***meson-cloud picture*** ...  
(and very unlike the large **unpolarized** sea-flavor asymmetry!)

## “Millenium Edition” Analysis of $\Delta q$

No more longitudinal-target data forthcoming, but some final analysis efforts ongoing:

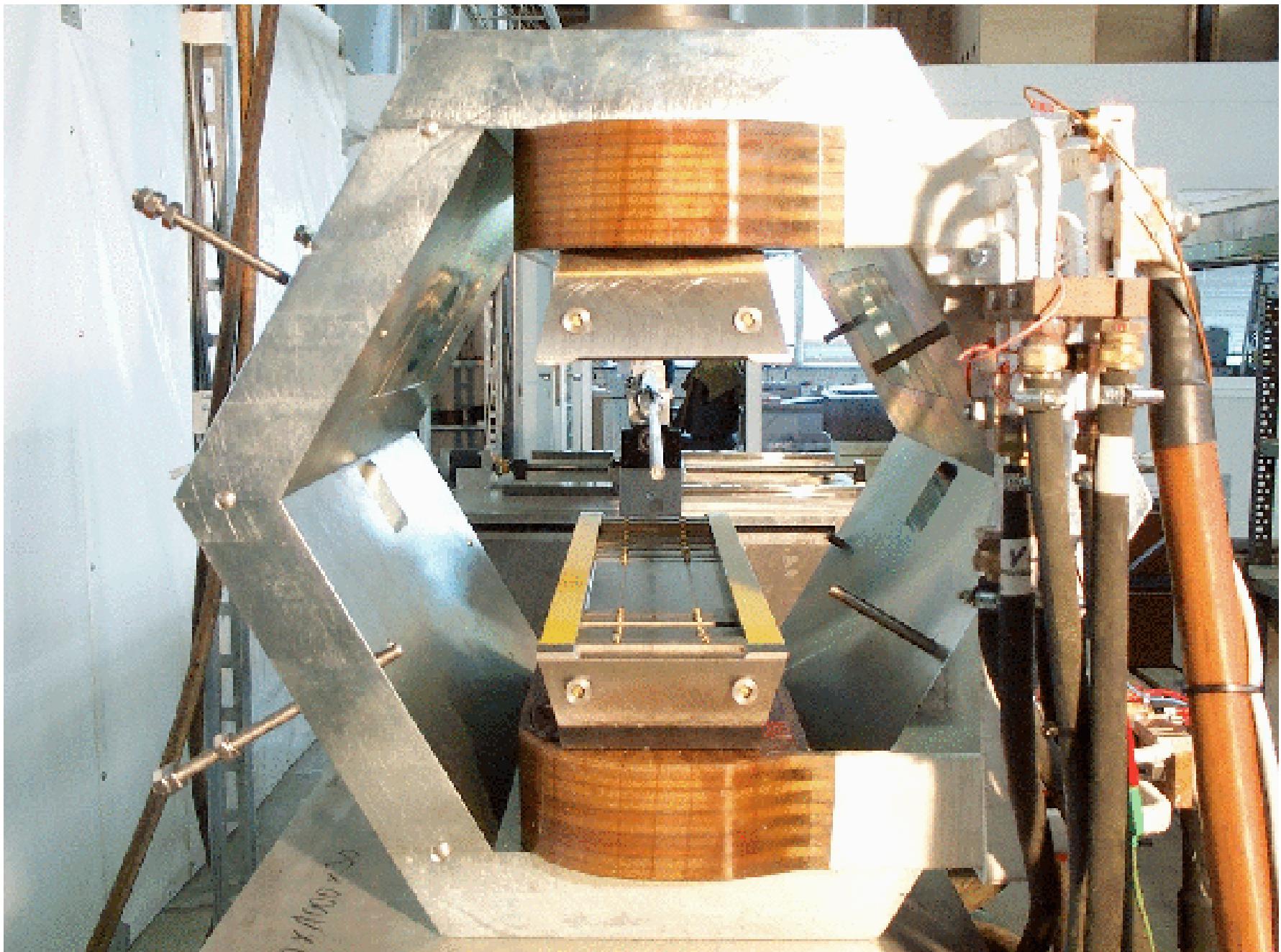
- Add in asymmetries for **unstable particles** ( $K_s, \Lambda, \dots$ )
- Painstaking determination of **systematic error** on **fragmentation model** in Monte Carlo (i.e. Lund parameters)  
→ current error = overestimate

*but many other physics topics arose during Run 1 ...*

## HERMES Run 2a: 2002 - 2005



*Transverse Hydrogen target installed in 2001*

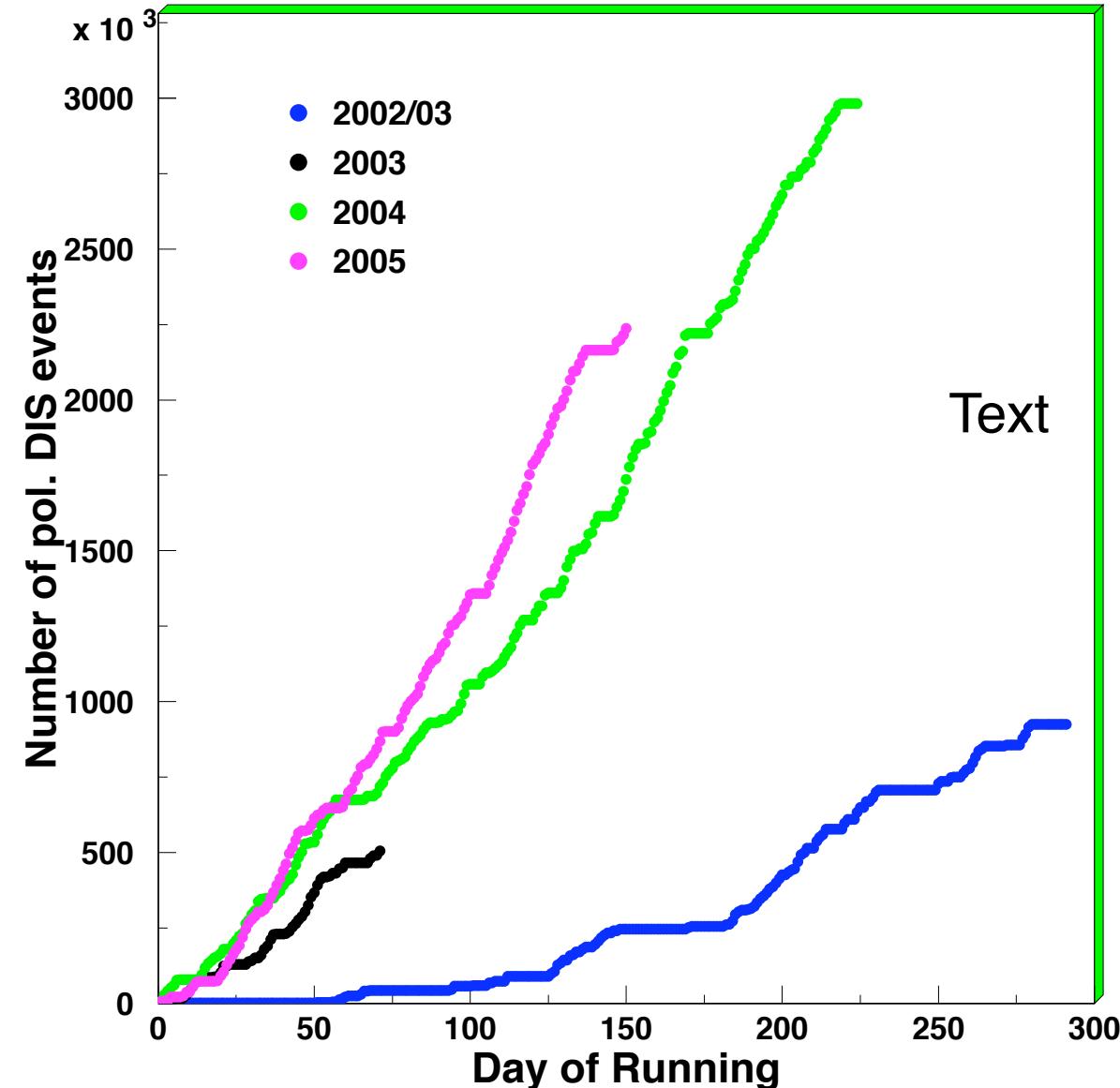


# HERMES Run 2a: 2002 - 2005



*Transverse Hydrogen target installed in 2001*

Integrated DIS HERA Run II (polarized)



## DIS Data Analyzed so Far

year	target	spin	# DIS
96–97	H	L	2.4 M
98–00	D	L	9.3 M ☺
02/03	H	T	0.7 M ☹
03–04	H	T	2.8 M ☺

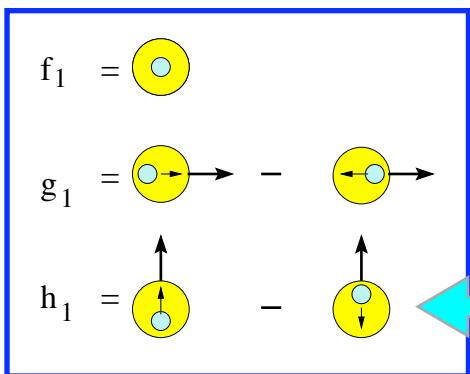
Run extended to **Nov 2005**,  
expect another  $\sim 4$  M DIS

**Main Idea:** access to

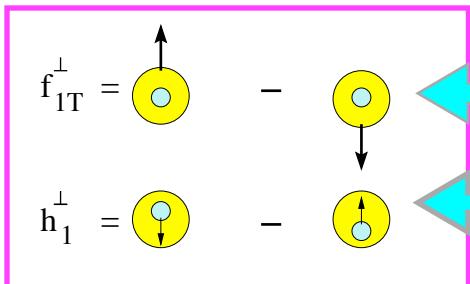
- transversity PDF
- transverse-momentum dependent (TMD) PDF's and fragmentation functions

# Functions surviving on integration over Transverse Momentum

## Distribution Functions



transversity



Sivers

Sokolov-Ternov?

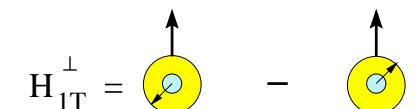
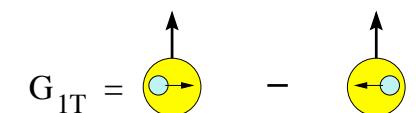
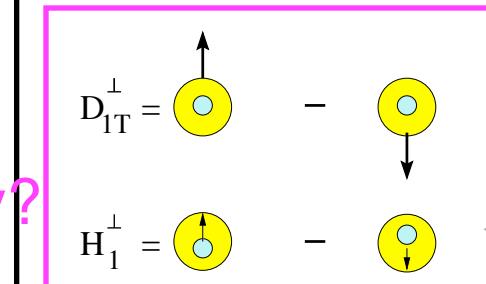
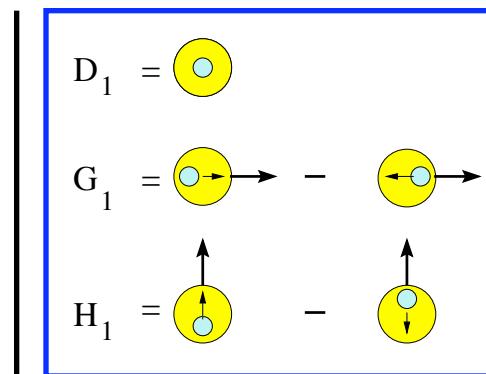


Functions Odd under naive Time Reversal

The others are sensitive to *intrinsic  $k_T$*  in the nucleon & in the fragmentation process

Mulders & Tangerman, NPB 461 (1996) 197

## Fragmentation Functions

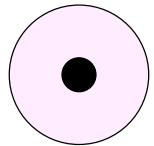


Collins

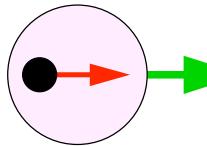
One T-odd function required to produce *single-spin asymmetries* in SIDIS

## Possible Mechanism #1: The “Collins Effect”

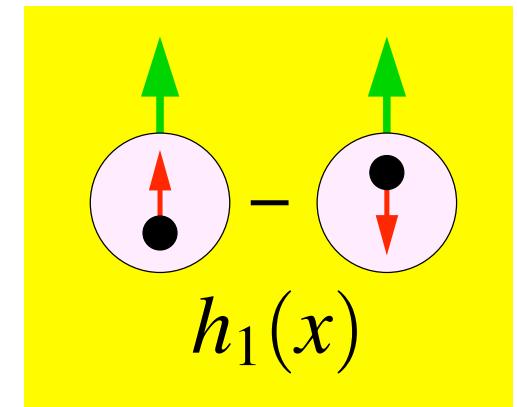
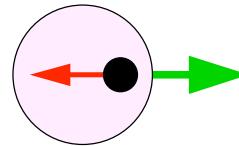
Need an ordinary distribution function ... **transversity**



$$q(x)$$



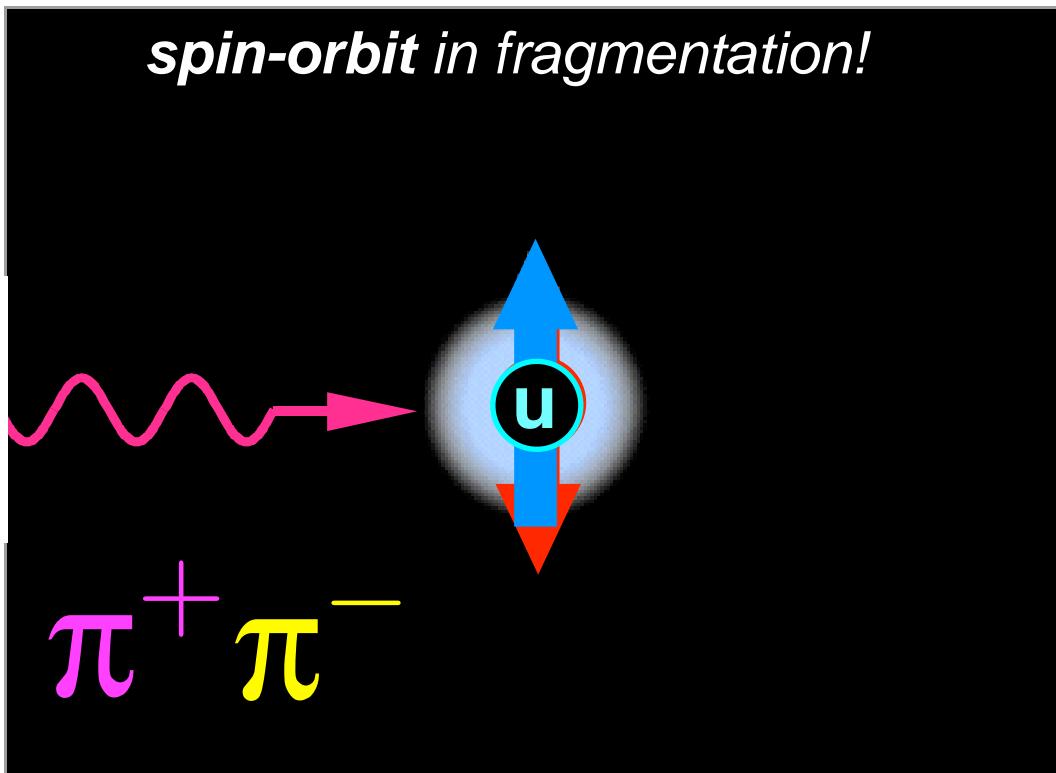
$$\Delta q(x)$$



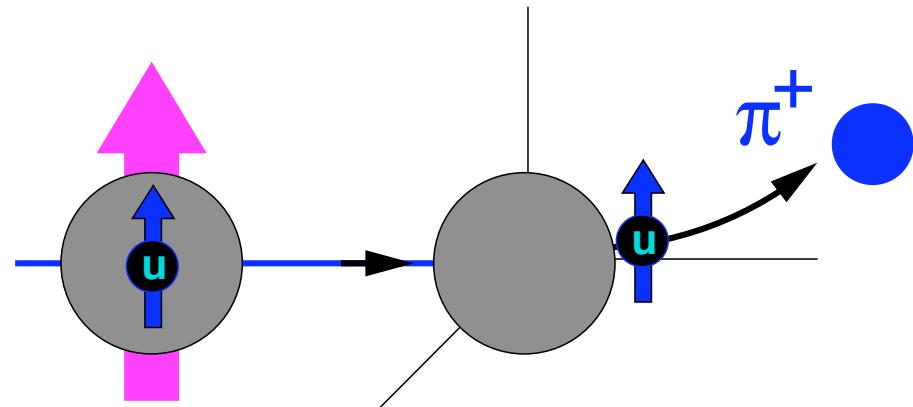
... with a new, T-odd “Collins” fragmentation function

$$H_1^\perp(z, p_T)$$

*spin-orbit in fragmentation!*



E704 effect:



$$h_1(x) \otimes H_1^\perp(z, p_T)$$

## Possible Mechanism #2: The “Sivers Effect”

Need the ordinary fragmentation function

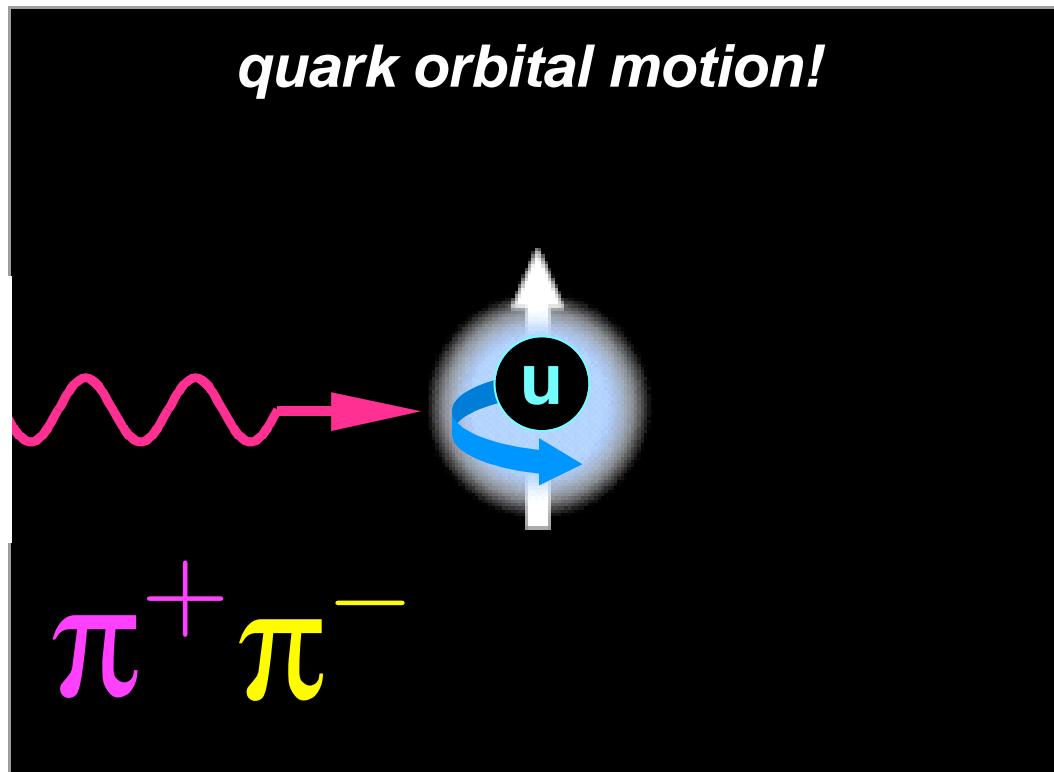
$$D_1(z)$$

... with a new, T-odd “Sivers” distribution function

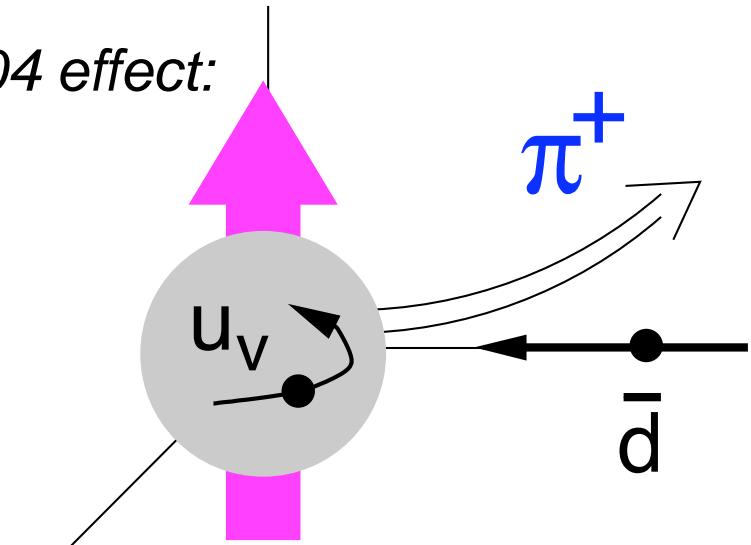
$$f_{1T}^\perp(x, k_T)$$

Phenomenological model of **Meng & Chou**:

Forward  $\pi^+$  produced from **orbiting valence-u quark** by recombination at front surface of beam protons

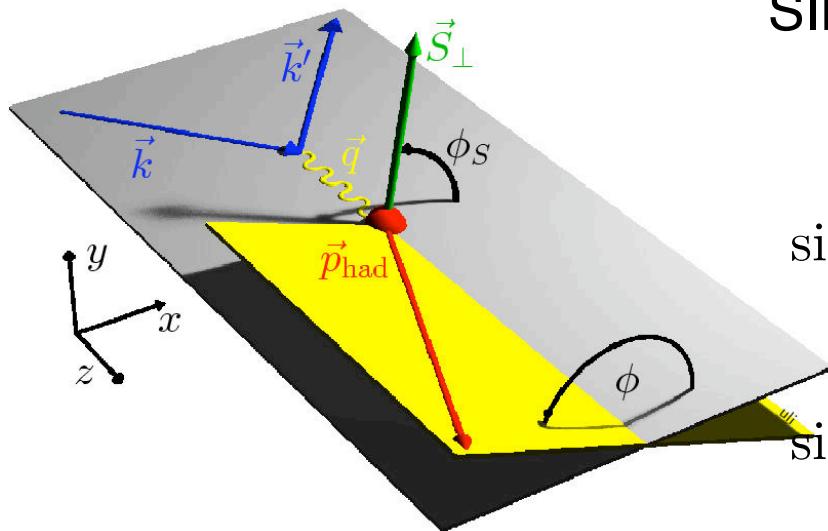


E704 effect:



$$f_{1T}^\perp(x, k_T) \otimes D_1(z)$$

# T-odd Distribution vs Fragmentation Function

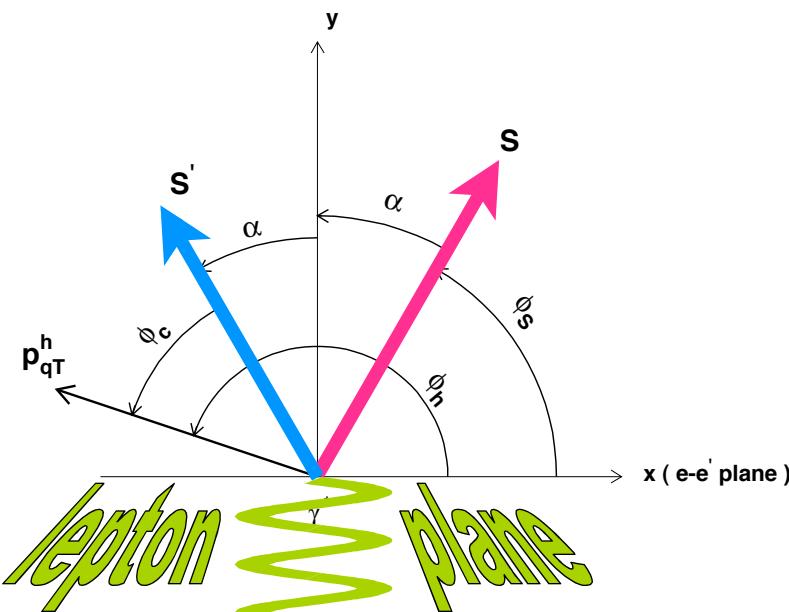


SIDIS xsec with *transverse target* polarization has *two* similar terms:

$$\sin(\phi_h^l + \phi_S^l) \Rightarrow h_1 = \begin{array}{c} \uparrow \\ \circlearrowleft \end{array} - \begin{array}{c} \uparrow \\ \circlearrowright \end{array} \otimes H_1^\perp = \begin{array}{c} \uparrow \\ \circlearrowleft \end{array} - \begin{array}{c} \bullet \\ \circlearrowright \end{array}$$

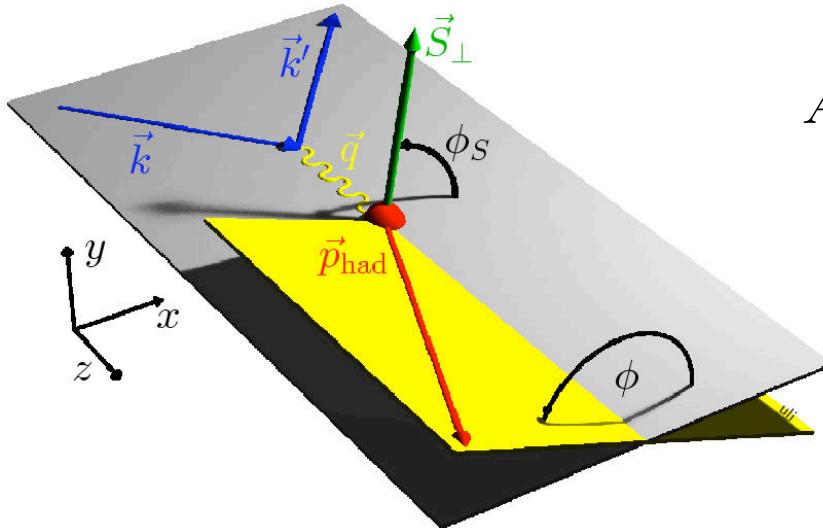
$$\sin(\phi_h^l - \phi_S^l) \Rightarrow f_{1T}^\perp = \begin{array}{c} \uparrow \\ \circlearrowleft \end{array} - \begin{array}{c} \bullet \\ \circlearrowright \end{array} \otimes D_1 = \begin{array}{c} \bullet \\ \circlearrowright \end{array}$$

**separate Sivers and Collins mechanisms**



- $(\phi_h^l - \phi_S^l)$  = angle of hadron relative to **initial** quark spin
- $(\phi_h^l + \phi_S^l) = \pi + (\phi_h^l - \phi_S^{l'})$  = hadron relative to **final** quark spin

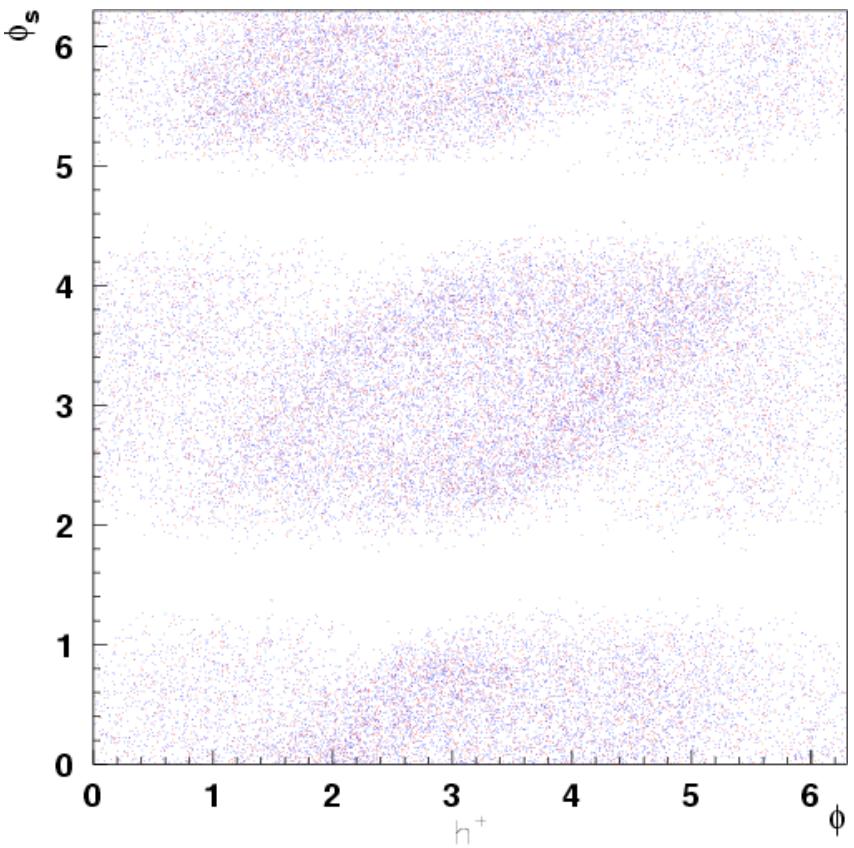
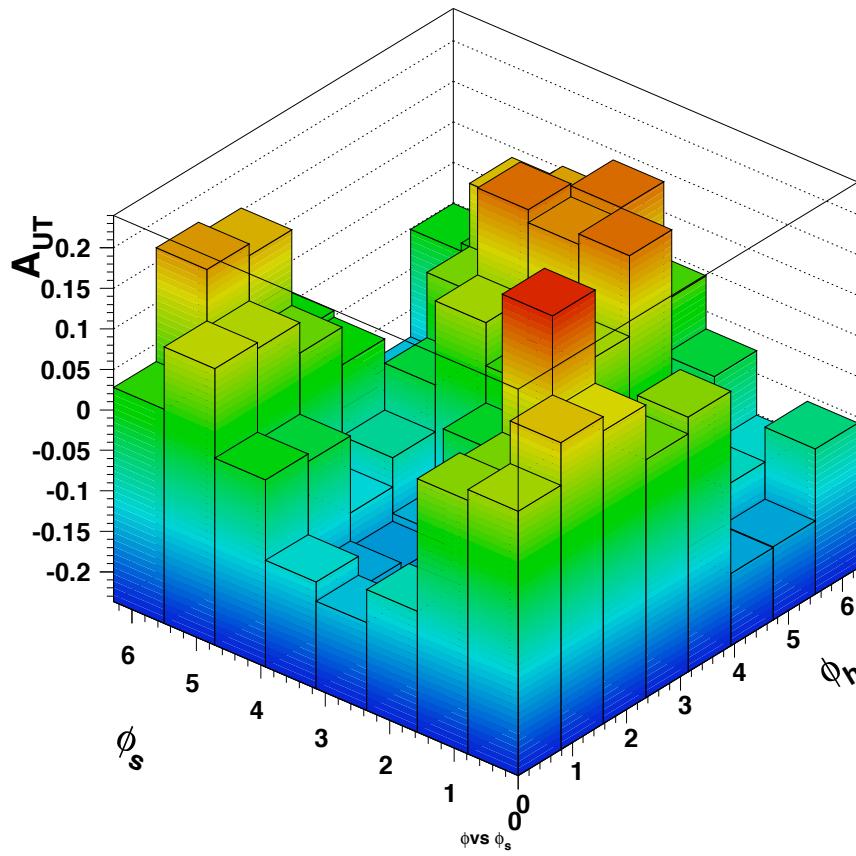
# Definition of Asymmetries and Moments



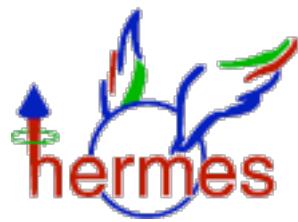
$$A_{\text{UT}}^h(\phi, \phi_S) = \frac{1}{|P_T|} \frac{N_h^\uparrow(\phi, \phi_S) - N_h^\downarrow(\phi, \phi_S)}{N_h^\uparrow(\phi, \phi_S) + N_h^\downarrow(\phi, \phi_S)}$$

$$= A_{\text{UT}}^{\text{Col}} \sin(\phi + \phi_S) + A_{\text{UT}}^{\text{Siv}} \sin(\phi - \phi_S)$$

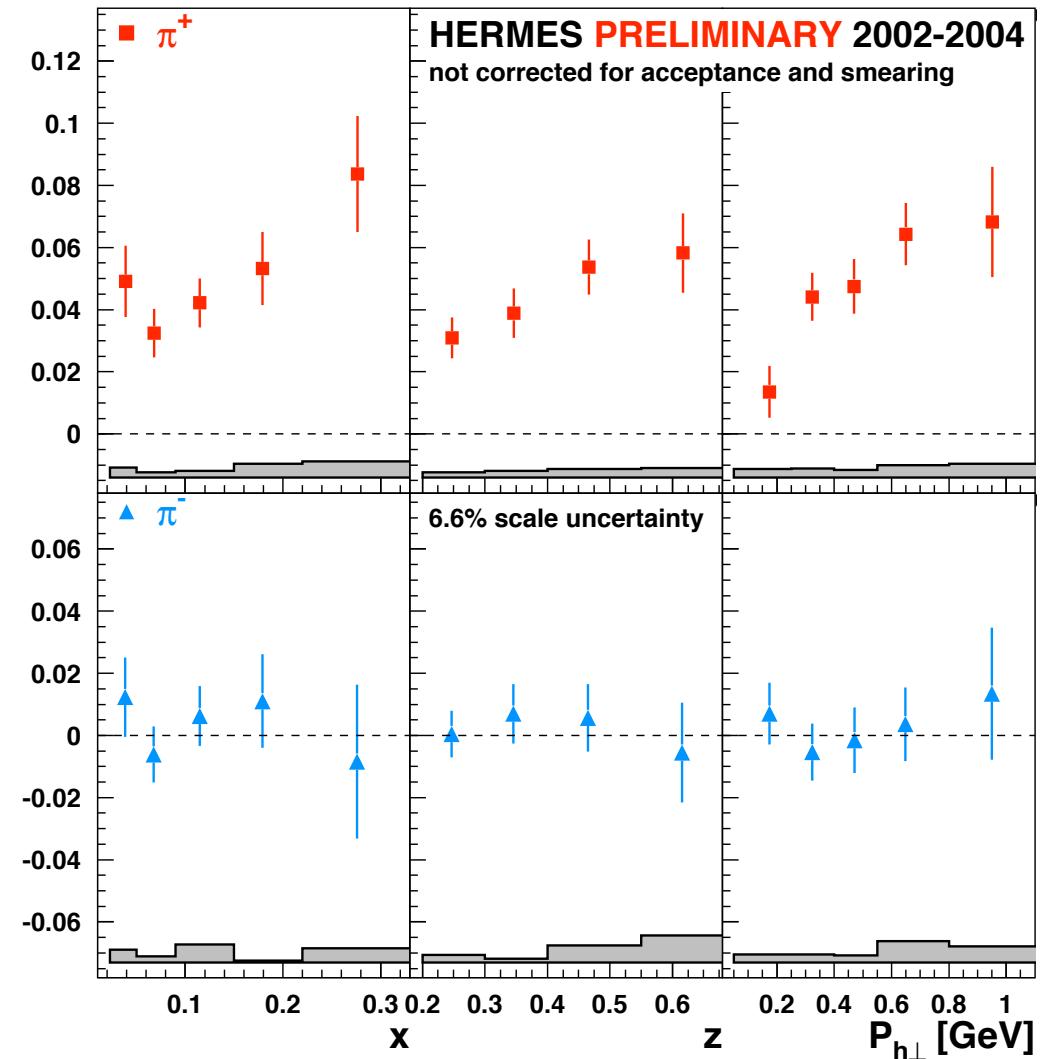
→ fit amplitudes **simultaneously**  
 (prevents mixing of effects by acceptance)



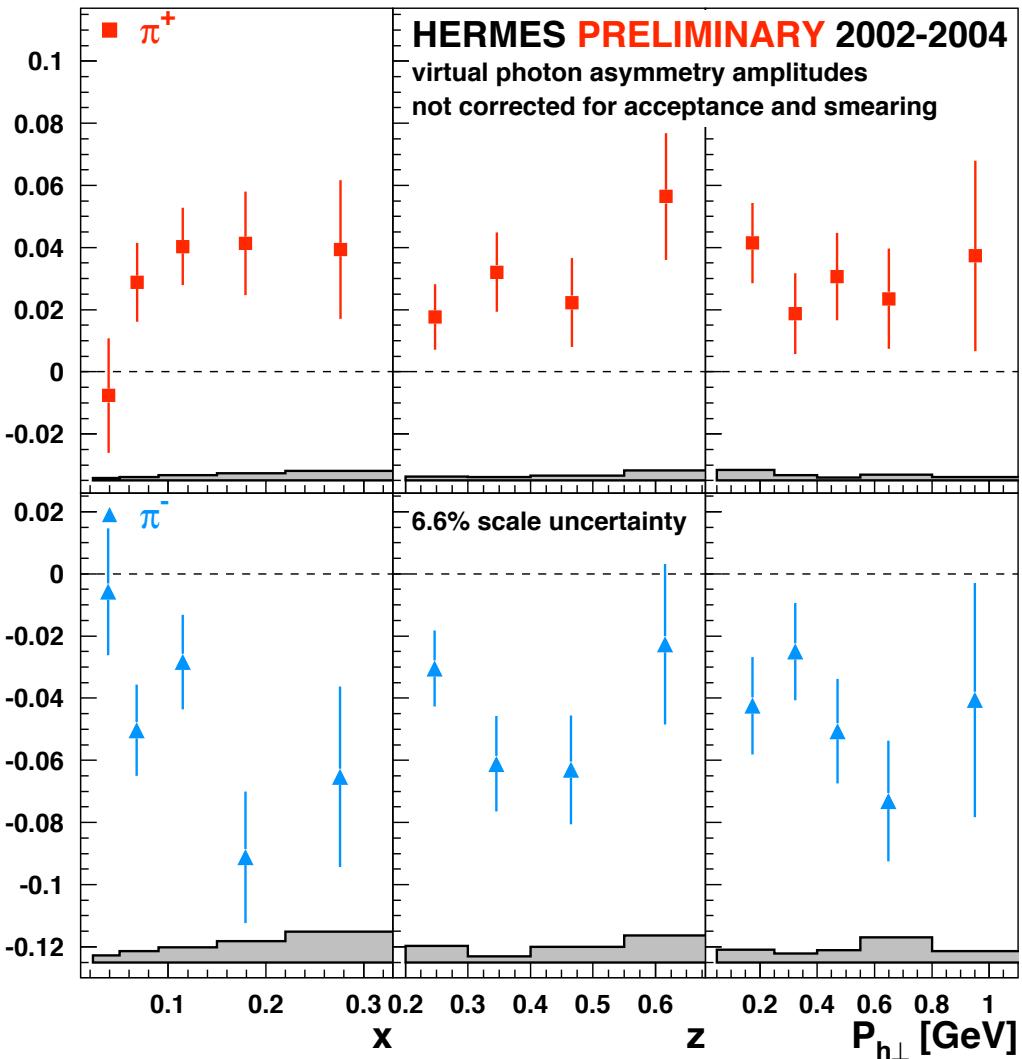
# New Results from 2002–2004: H $\uparrow$ Target



## Sivers Moments for $\pi^+ \pi^-$



## Collins Moments for $\pi^+ \pi^-$



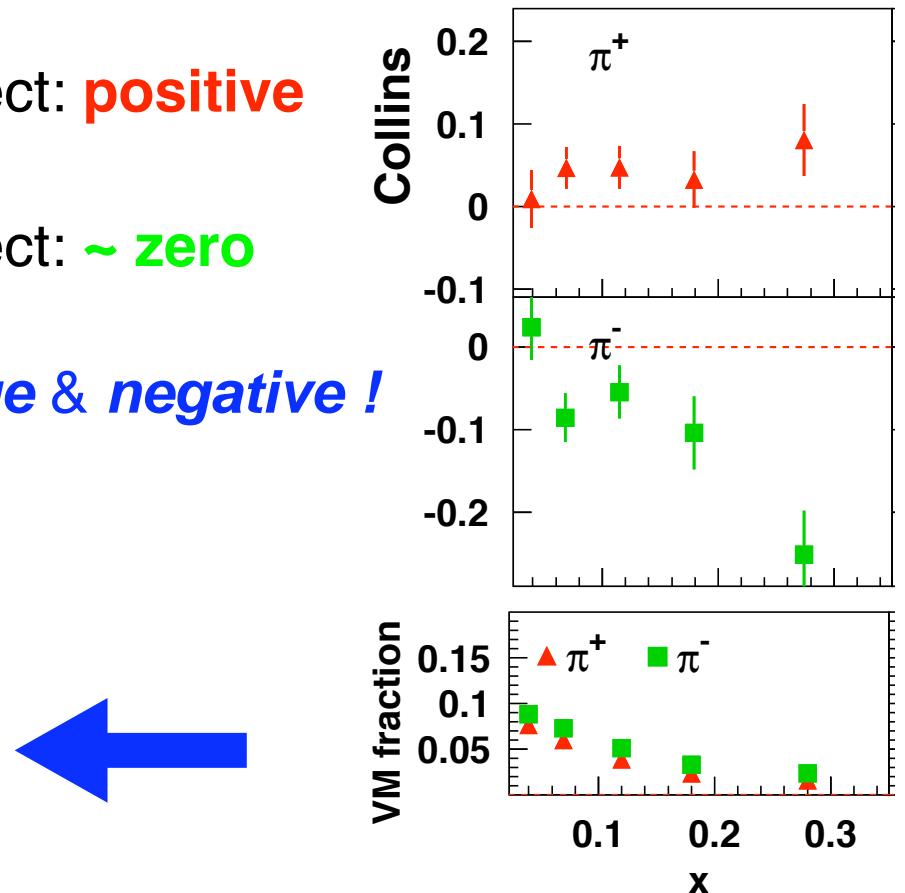
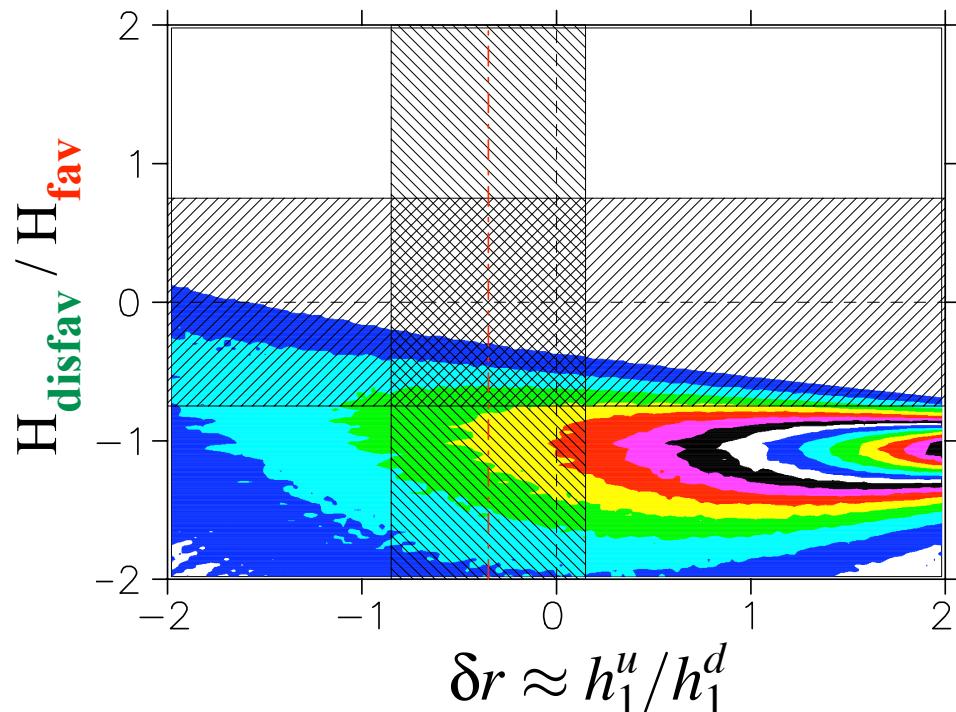
# Why are the Collins $\pi^-$ asymmetries so large?



DIS on proton target always dominated by *u-quark scattering*

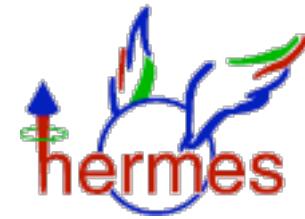
- $A_{\text{Col}}^{\pi^+} \sim h_1^u H_{1,\text{favored}}^\perp$  ... expect: **positive**
- $A_{\text{Col}}^{\pi^-} \sim h_1^u H_{1,\text{disfavored}}^\perp$  ... expect:  **$\sim$  zero**

Data indicate ***disfavored*** CollinsFF is ***large & negative*** !



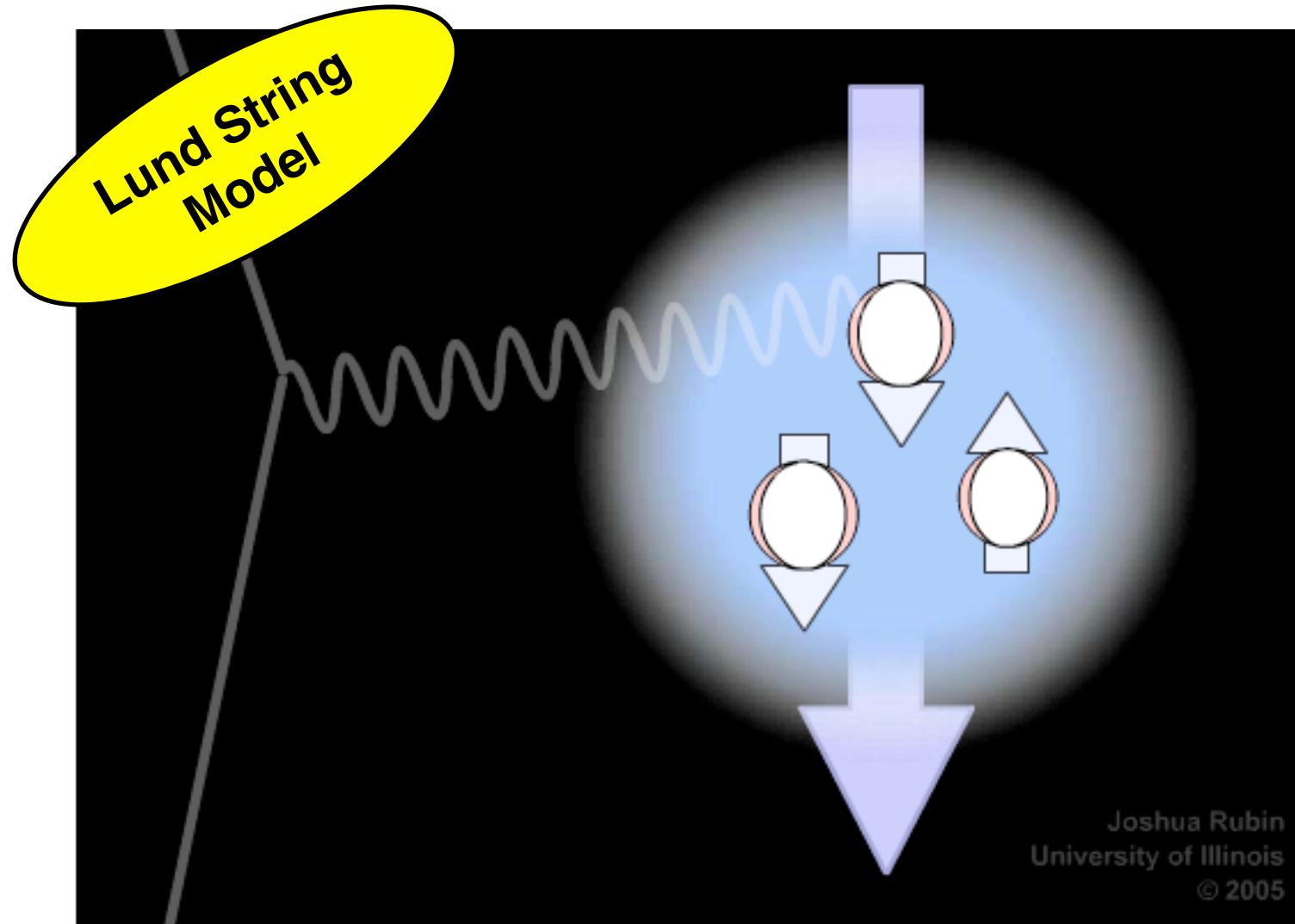
Map out solution space ...  
find  $H_{\text{disfav}} \approx -H_{\text{fav}}$

# Understanding the Collins Effect

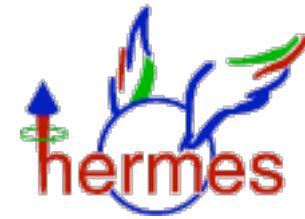


The Collins function exists!  $\rightarrow$  spin-orbit correlations in  $\pi$  formation

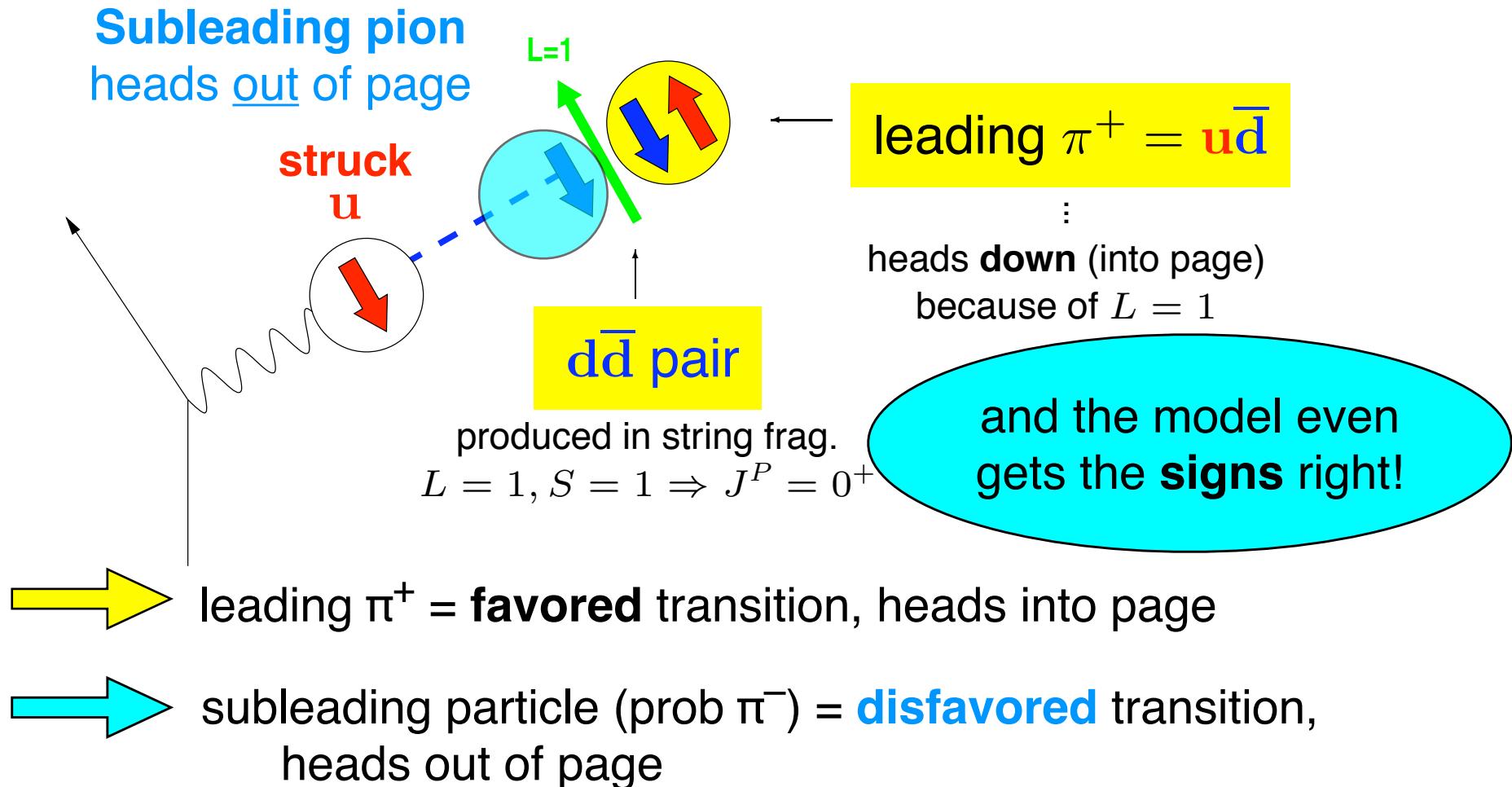
*Is the Artru mechanism responsible?*



# Interpretation of Collins Results



Artru model, based on phenomenological **Lund string-fragmentation model** and  **$^3P_0$  hypothesis** for qqbar-pair formation

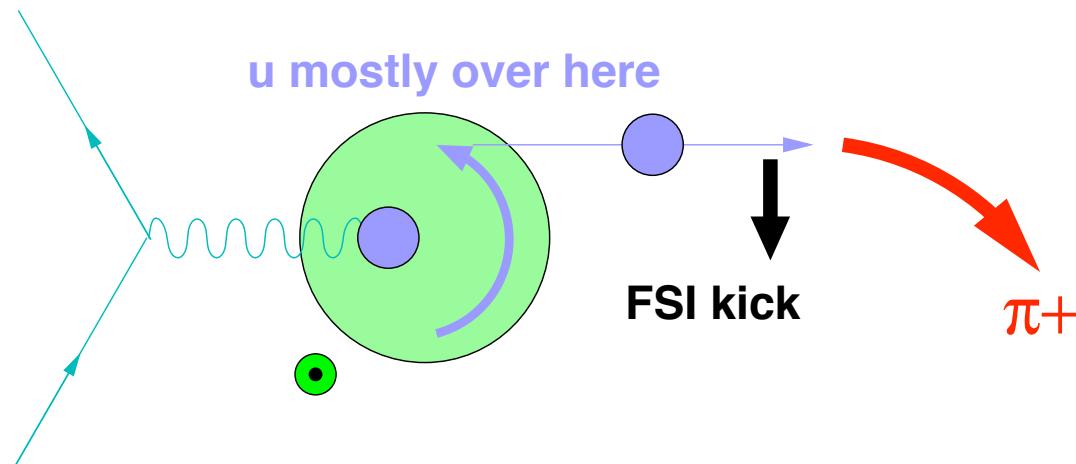


## Dynamical Models for Sivers Mechanism

Many models suggest  $L_u > 0 \dots$

### M. Burkardt: Chromodynamic lensing

**Electromagnetic coupling**  $\sim (J_0 + J_3)$  **stronger for oncoming quarks**



We observe  $\langle \sin(\phi_h^l - \phi_S^l) \rangle_{\text{UT}}^{\pi^+} > 0$

(and opposite for  $\pi^-$ )

∴ for  $\phi_S^l = 0$ ,  $\phi_h^l = \pi/2$  preferred

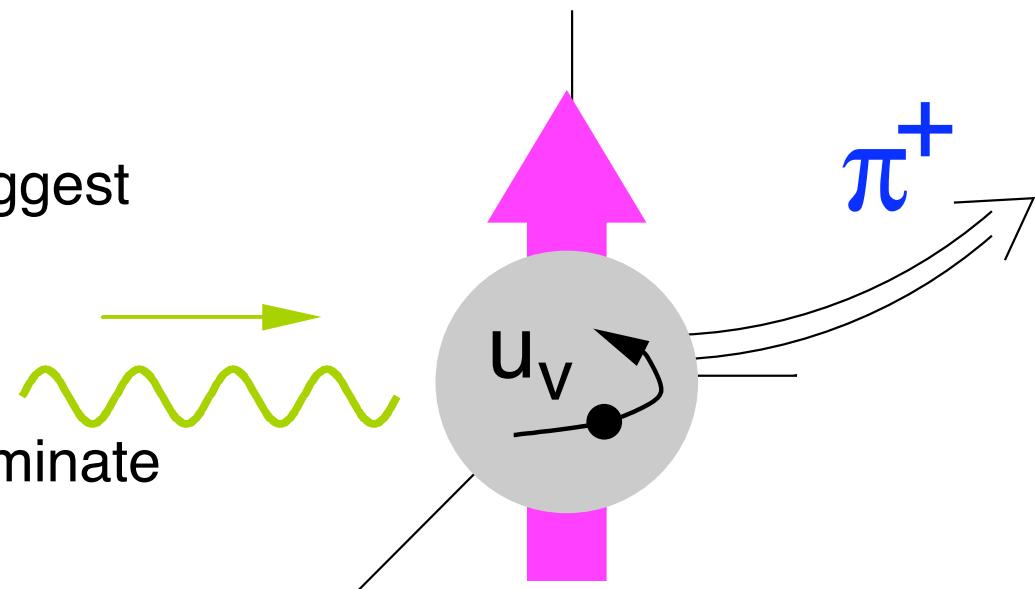
*Model agrees!*

### D. Sivers: Jet Shadowing

Parton energy loss considerations suggest  
**quenching of jets from  
“near” surface of target**

→ quarks from “far” surface should dominate

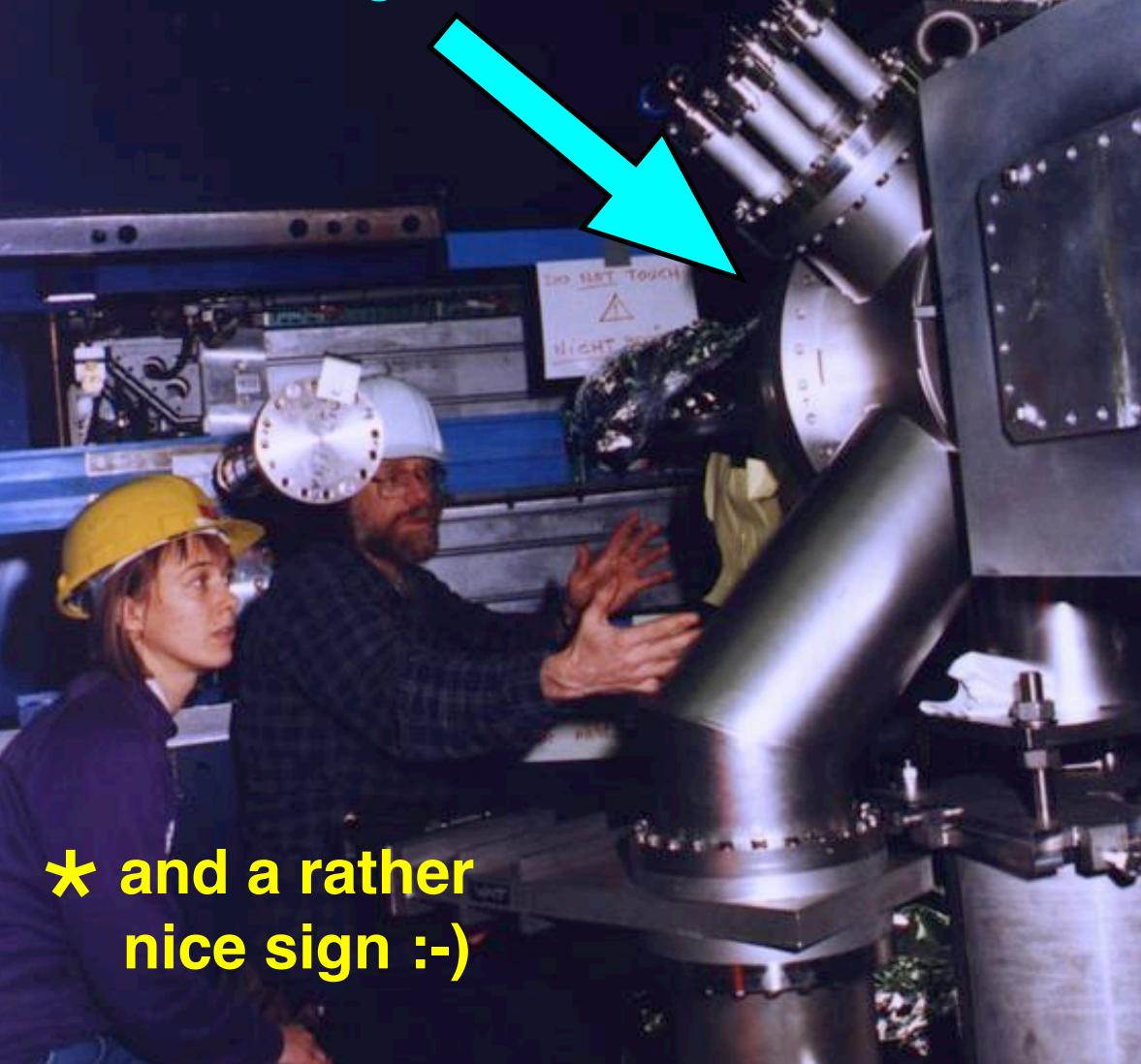
Opposite sign to data ...





## Run 2a: SIDIS Expectations

The Noble ABS: target scattering chamber



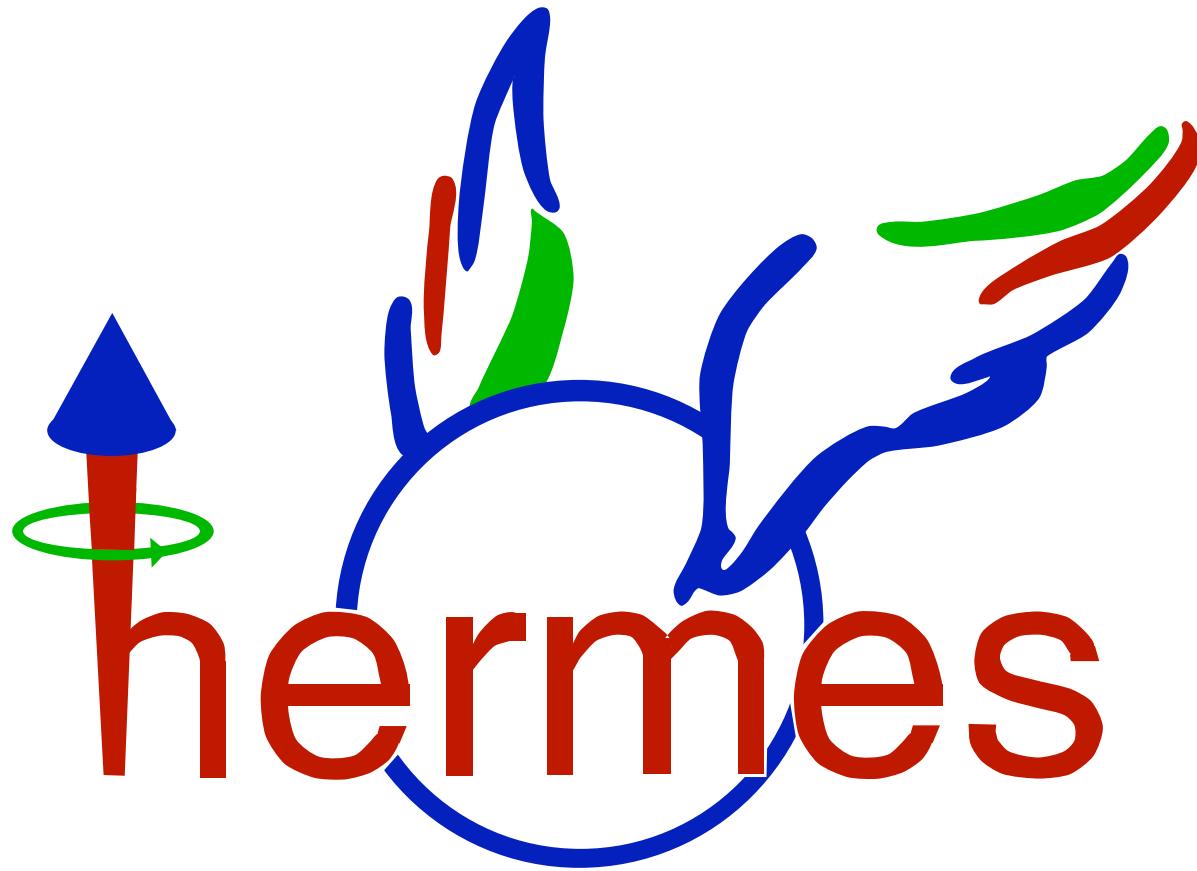
\* and a rather nice sign :-)

- Statistics of presently-analyzed Collins & Sivers asymmetries will **double** by end of 2005 run
- BELLE data on Collins FF ⇒ **transversity** measurement
- **Sivers distributions** under analysis via **purity method** (fragm. functions known)  
... from first 0.7 M DIS, first glimpse of first moments:

$$f_{1T}^{\perp(1)u} + \frac{1}{4} f_{1T}^{\perp(1)\bar{d}} = -0.044 \pm 0.016$$

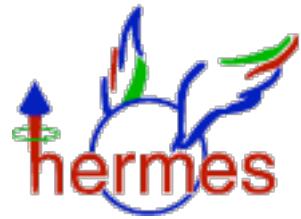
$$f_{1T}^{\perp(1)d} + \frac{1}{4} f_{1T}^{\perp(1)\bar{u}} = +0.074 \pm 0.066$$

(meas x-range, stat errors only)



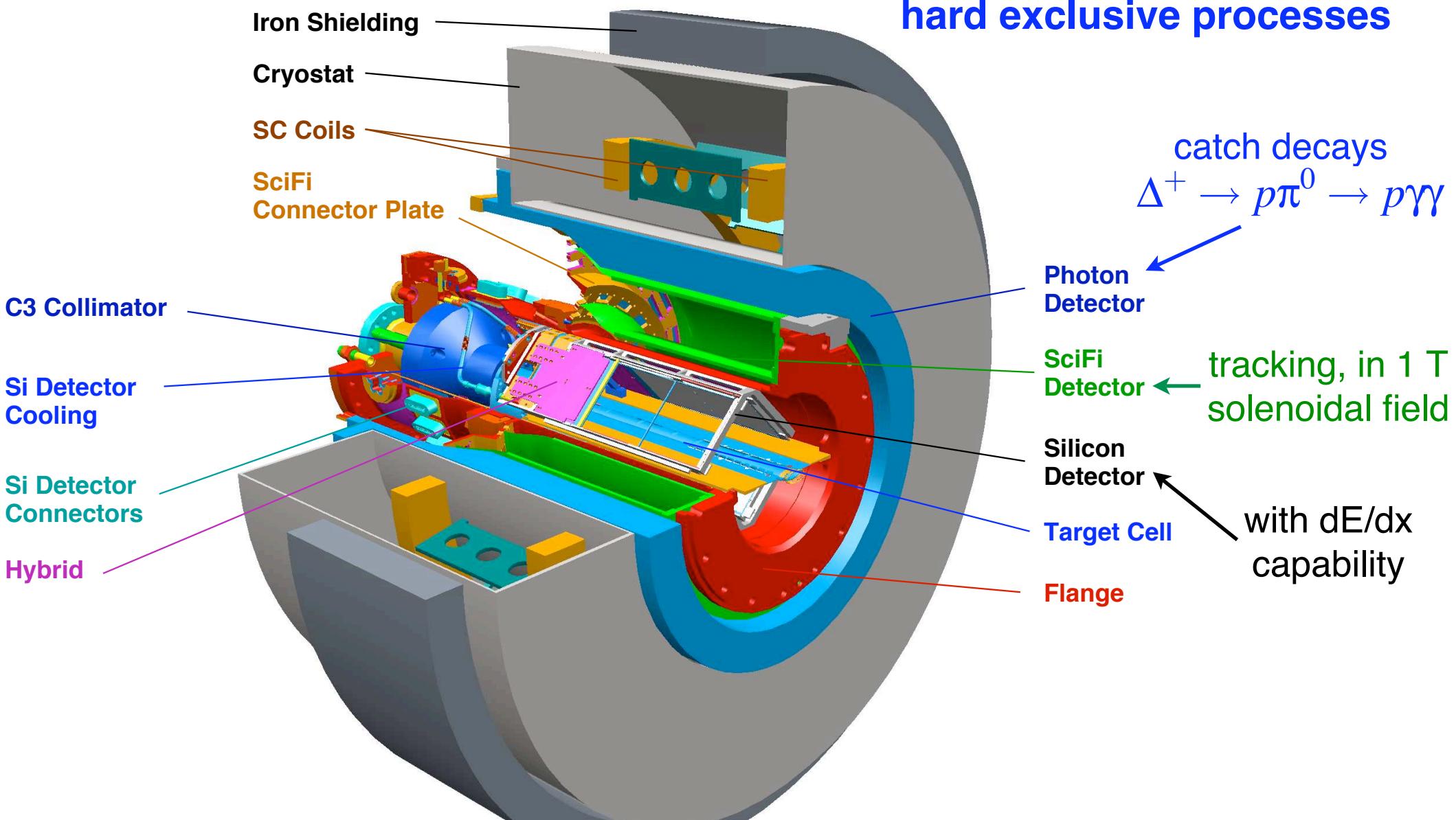
**“Home of the flying chicken”**

*Then in Dec 2005 ...*



## Recoil Detector Installation

Purpose: detect recoiling nucleons or resonances for measurement of  
**hard exclusive processes**

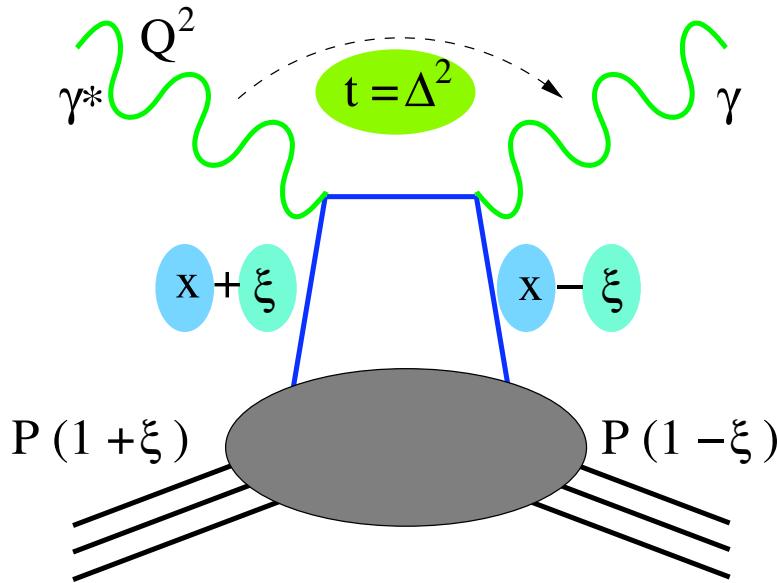


# Generalized Parton Distributions

Analysis of hard exclusive processes leads to a new class of parton distributions

Cleanest example: Deeply Virtual Compton scattering

**DVCS**



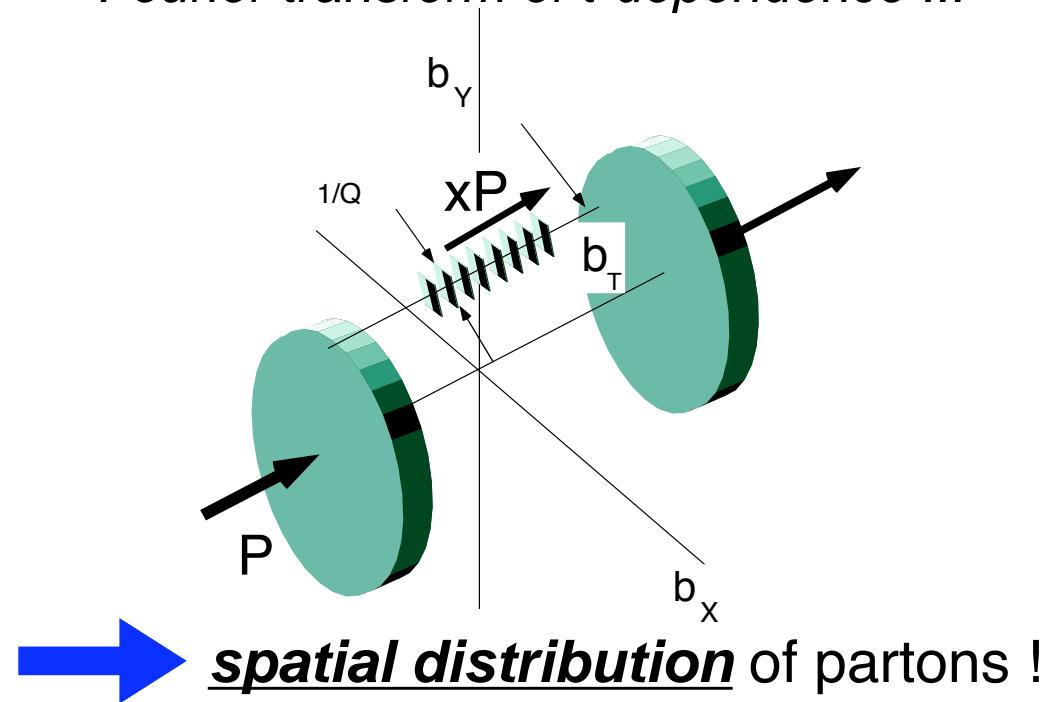
- $x$ : average quark momentum fraction
- $\xi$ : “skewing parameter” =  $x_1 - x_2$
- $t$ : 4-momentum transfer<sup>2</sup>

**Four new distributions = “GPDs”**

helicity conserving  $\rightarrow H(x, \xi, t), E(x, \xi, t)$   
 helicity flip  $\rightarrow \tilde{H}(x, \xi, t), \tilde{E}(x, \xi, t)$

**“Femto-photography” of the proton**

*Fourier transform of  $t$ -dependence ...*



- **DIS structure functions:**  
forward limit ( $\xi = 0, t = 0$ )

$$q(x) = H^q(x, \xi = 0, t = 0)$$

$$\Delta q(x) = \tilde{H}^q(x, \xi = 0, t = 0)$$

Connection to  
many observables

- **Elastic form factors:**  
first moments in  $x$

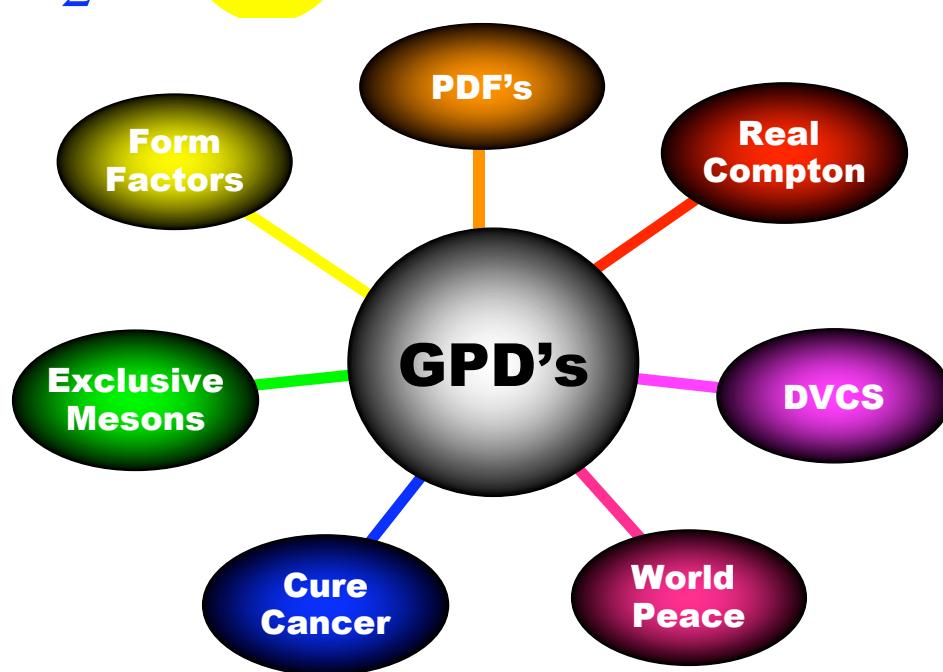
$$F_1^q(t) = \int_{-1}^1 dx H^q(x, \xi, t) \quad F_2^q(t) = \int_{-1}^1 dx E^q(x, \xi, t)$$

$$G_A^q(t) = \int_{-1}^1 dx \tilde{H}^q(x, \xi, t) \quad G_P^q(t) = \int_{-1}^1 dx \tilde{E}^q(x, \xi, t)$$

$$J^q = \frac{1}{2} \int_{-1}^1 x dx [H^q(x, \xi, t = 0) + E^q(x, \xi, t = 0)]$$

**→ *model-independent access to  $L$  !***

$$J^q = \frac{1}{2} \Delta \Sigma + L^q$$



Note connection of  $H, E$  to  
Dirac, Pauli form factors ...  
and their connection to  
nucleon magnetic moment:

$$F_1^N(0) + F_2^N(0) = \mu_N$$

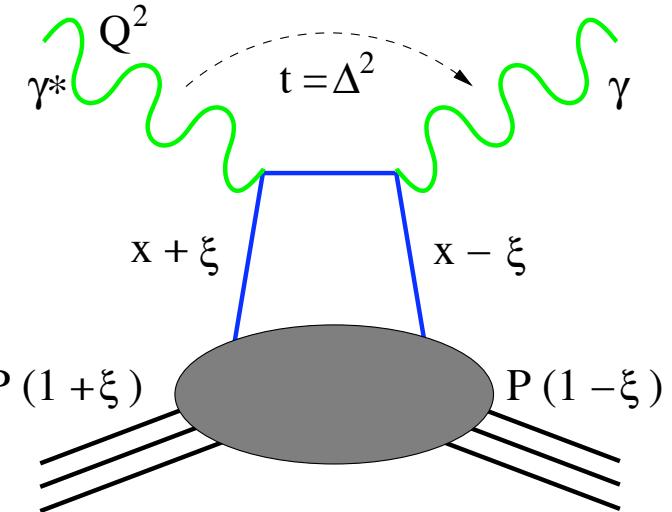
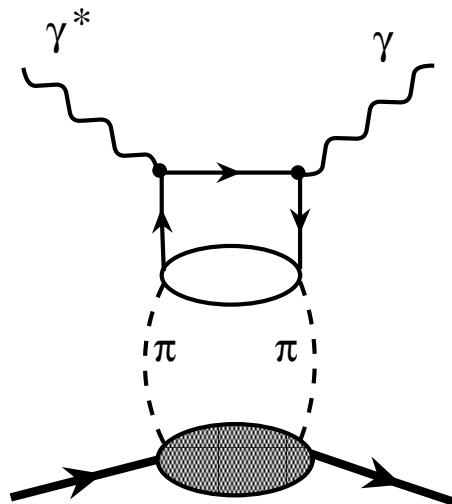
# Modelling the GPD's

- **$t$ -dependence** from elastic form factors
- **$\xi$ - (skewedness) and  $x$ - dependence**  
→ interpolate between 2 regions:

- $|x| > \xi$   
→  $x_1, x_2$  both  $> 0$  (quarks)  
or both  $< 0$  (antiquarks)
- ⇒ PDF's recovered in limit  $\boxed{\xi \rightarrow 0}$

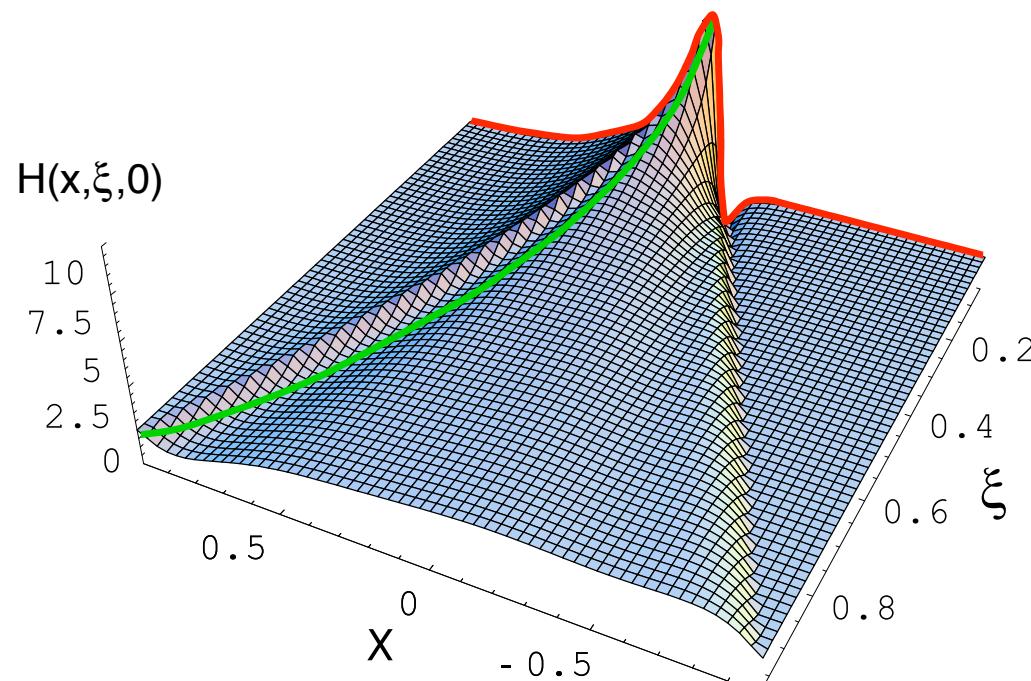
- $|x| < \xi$   
→ see correlation  
between  $q$  and  $\bar{q}$
- ⇒ “meson-like”  
distributions as

$\boxed{\xi \rightarrow 1}$



## Model of $H^d(x, \xi, t = 0)$ (forward limit)

Vanderhaeghen, Guichon, Guidal, PRD 60 (99) 094017

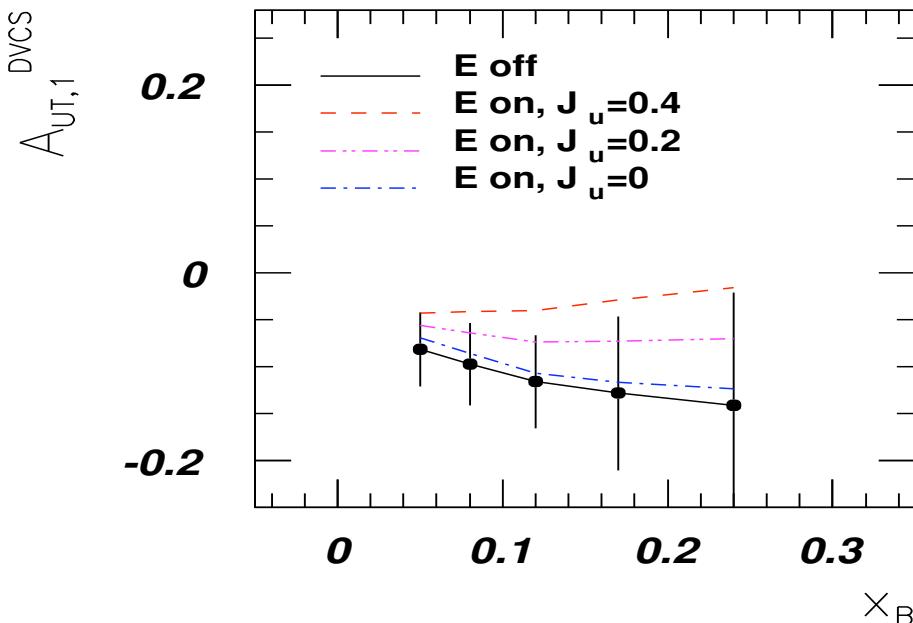


## Many exclusive channels measured, & more under study

### DVCS

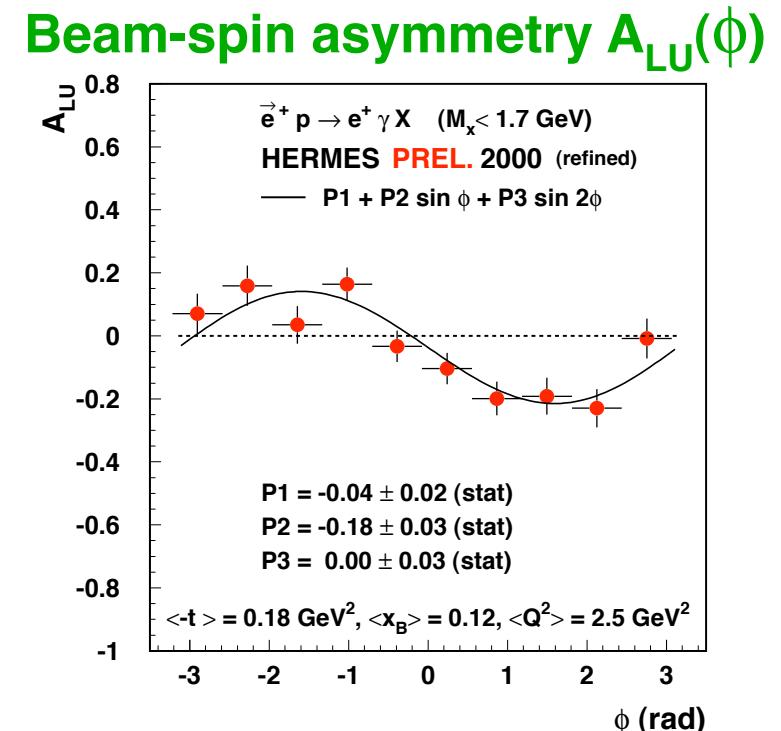
- Longitudinal beam-spin asym  $\rightarrow \text{Im}(H)$
- Beam-charge asymmetry  $\rightarrow \text{Re}(H)$
- Longitudinal target-spin asym  $\rightarrow \text{Im}(\tilde{H})$
- Transverse target-spin asym  $\rightarrow E, H$

Also many **exclusive meson** production channels offer access to GPD's

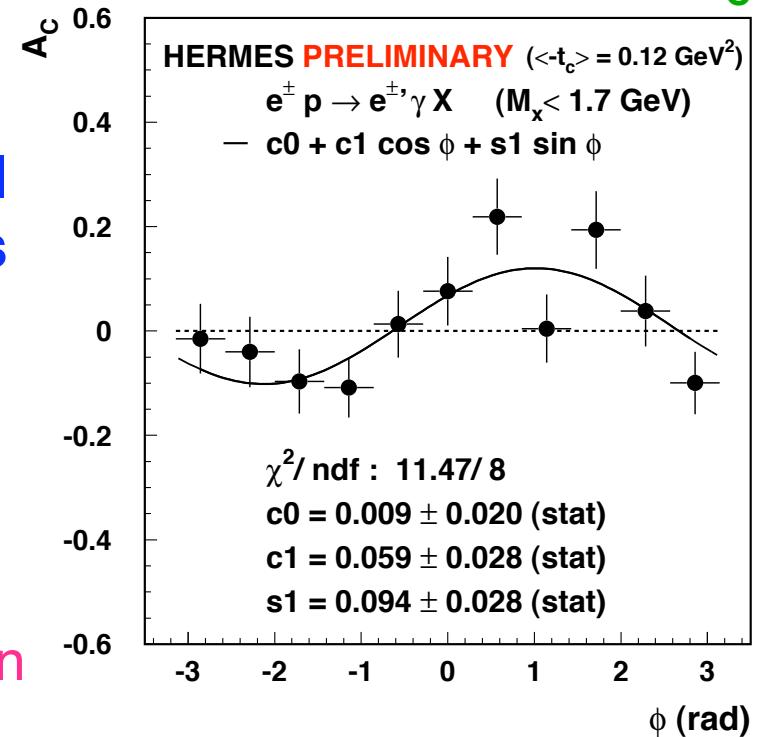


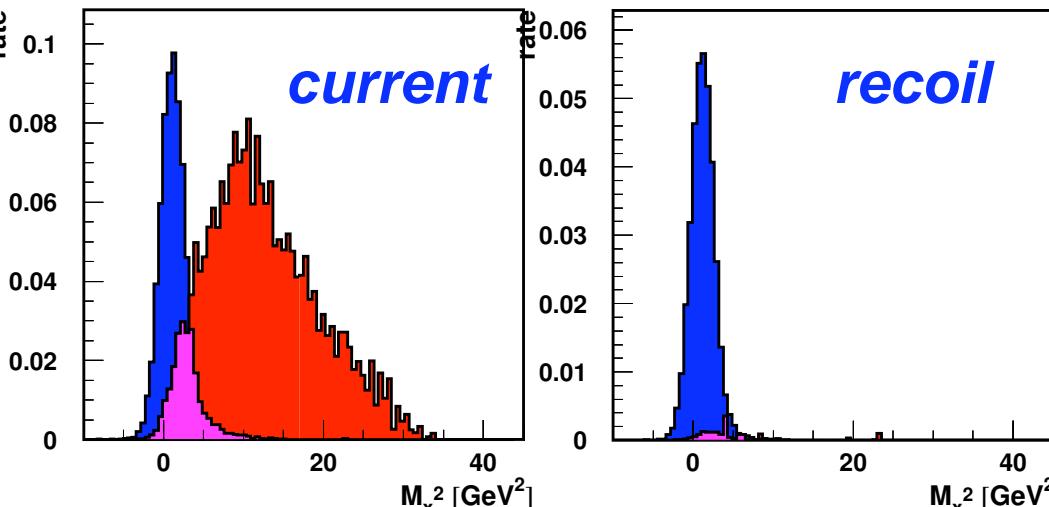
Constrain  
GPD model  
parameters  
in as many  
ways as  
possible!

◀ AUT projection

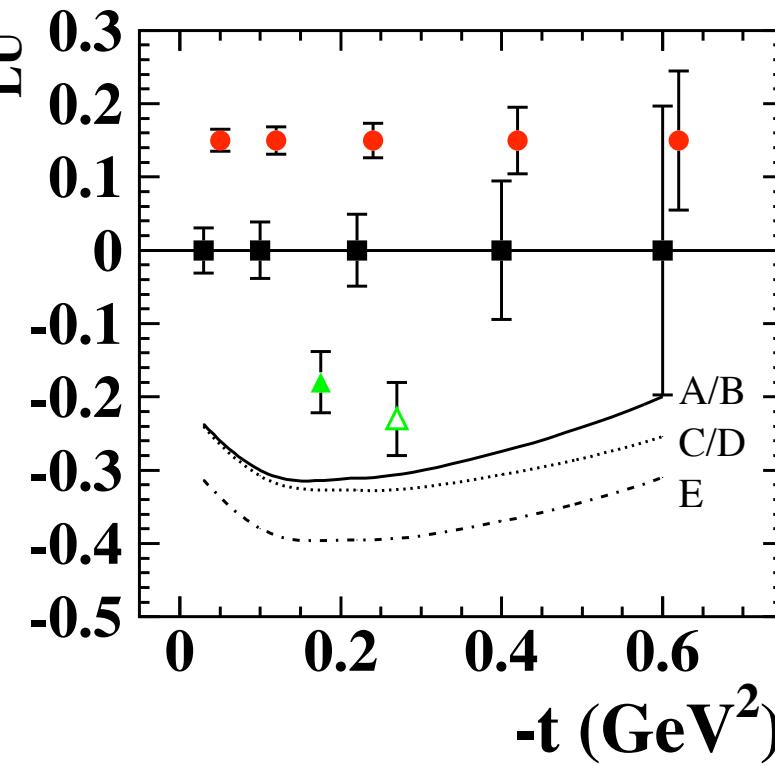
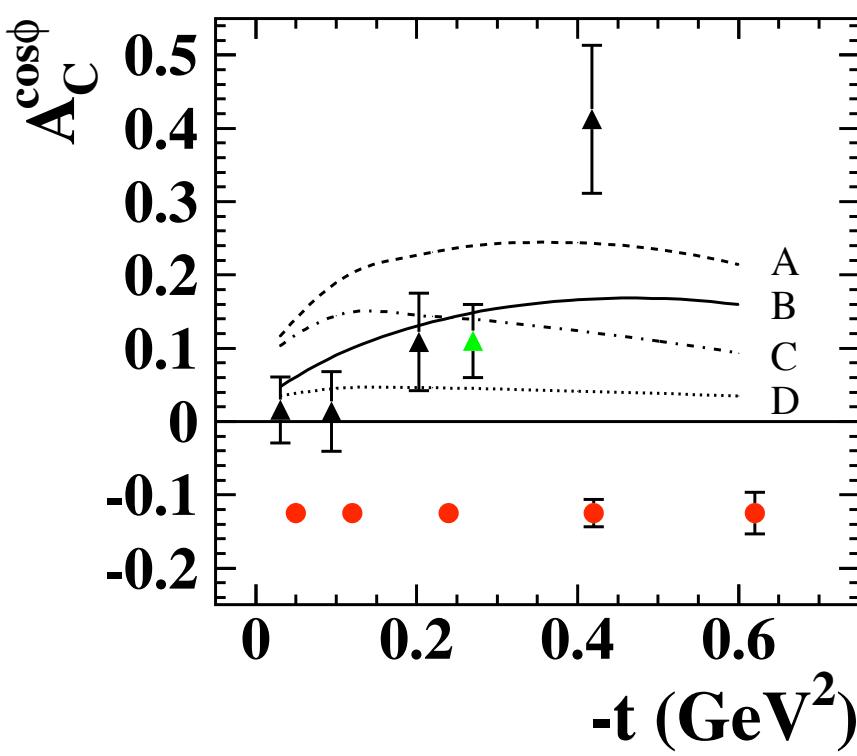


**Beam-charge asymmetry  $A_C(\phi)$**





- Run 1 published
- Run 1 precision (nearly done)
- Run 2 projection



## Recoil Detector Advantages

- **Exclusivity**: current missing-mass resolution  $\rightarrow \Delta$  contamination
- **t-resolution** greatly improved
- **Statistics**: order of magnitude more statistics for  $A_{LU}$  and  $A_C$  (high-density unpol'd targets!)